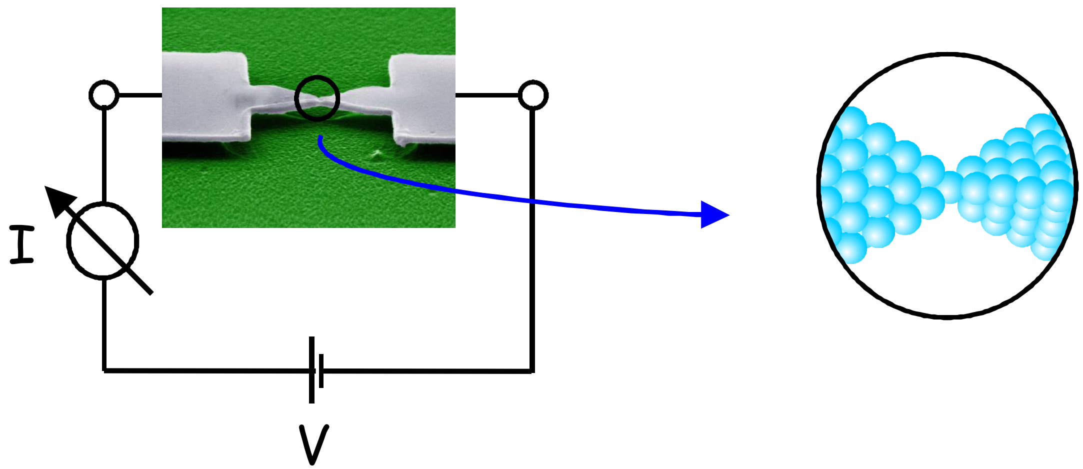
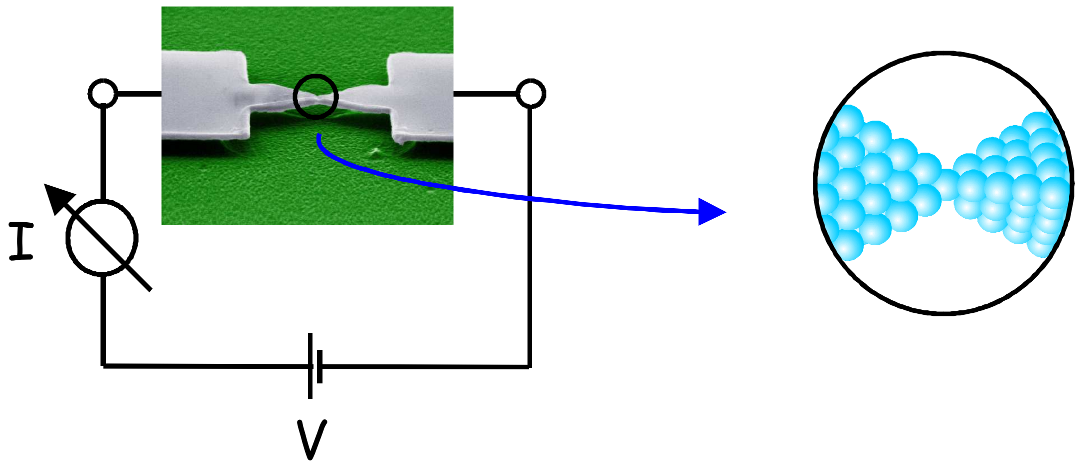
Electronic Transport through Single-Atom Contacts of Ferromagnetic Metals



Landauer formula: $G = 2e^2/h \sum_{n=1}^{N} \tau_n$

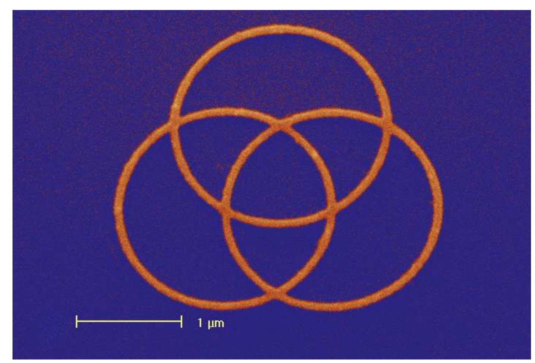
- What are the conduction channels?
- How many channels can a single-atom contact build?
- Are the channels spin-polarized?
- Are the transmission values quantized?

Electronic Transport through Single-Atom Contacts of Ferromagnetic Metals



People:
R. Arnold
C. Bacca
V. Kunej
H.-F. Pernau

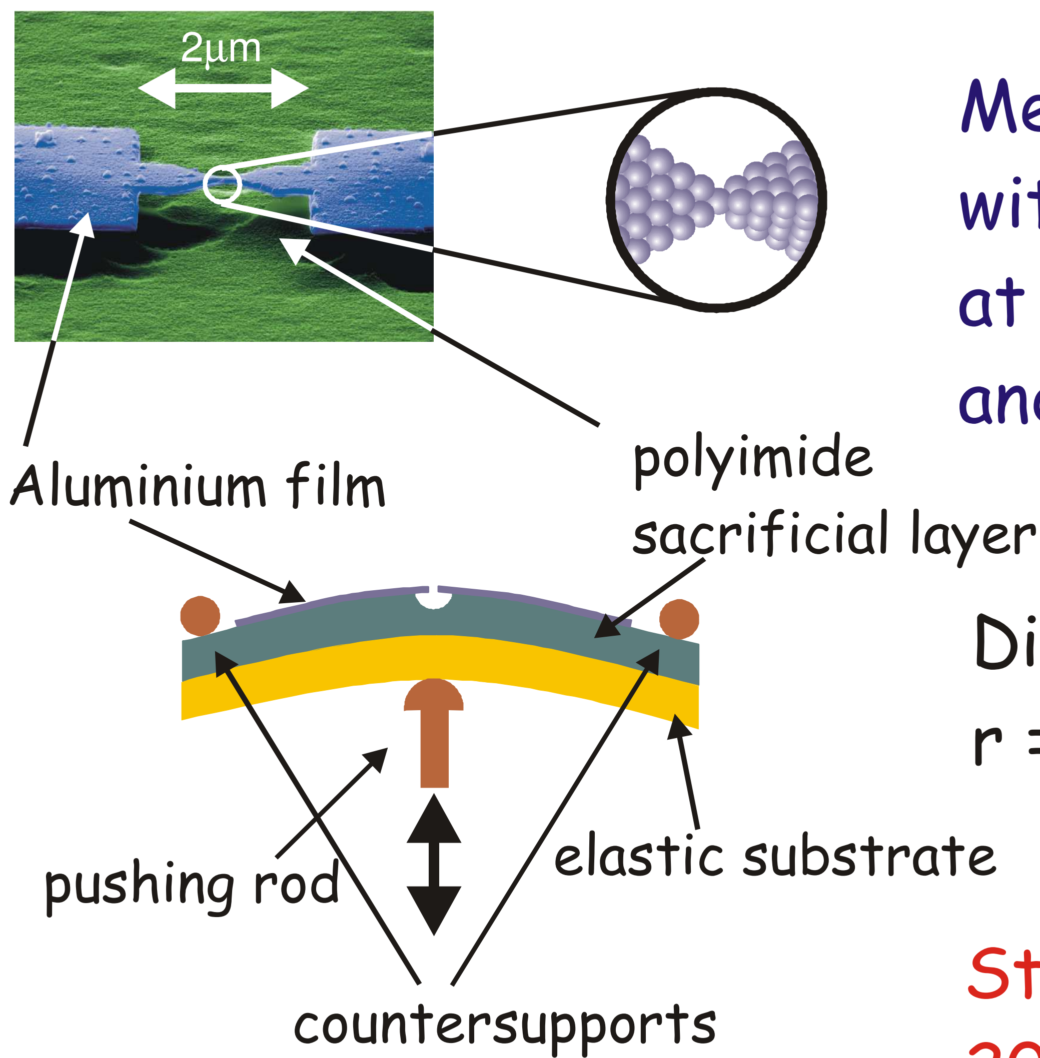
Landauer formula: $G = 2e^2/h \sum_{n=1}^{N} \tau_n$



Thanks to groups of:
C. Urbina (Saclay), J.C. Cuevas (Karlsruhe)
P. Leiderer, G. Ganteför, P. Nielaba (Konstanz),
H.v. Löhneysen (Karlsruhe), W. Belzig (Basel),
J.M. van Ruitenbeek (Leiden), N. Agrait (Madrid)

Financial support: DFG and Krupp Foundation

SUSPENDED NANOBRIDGE



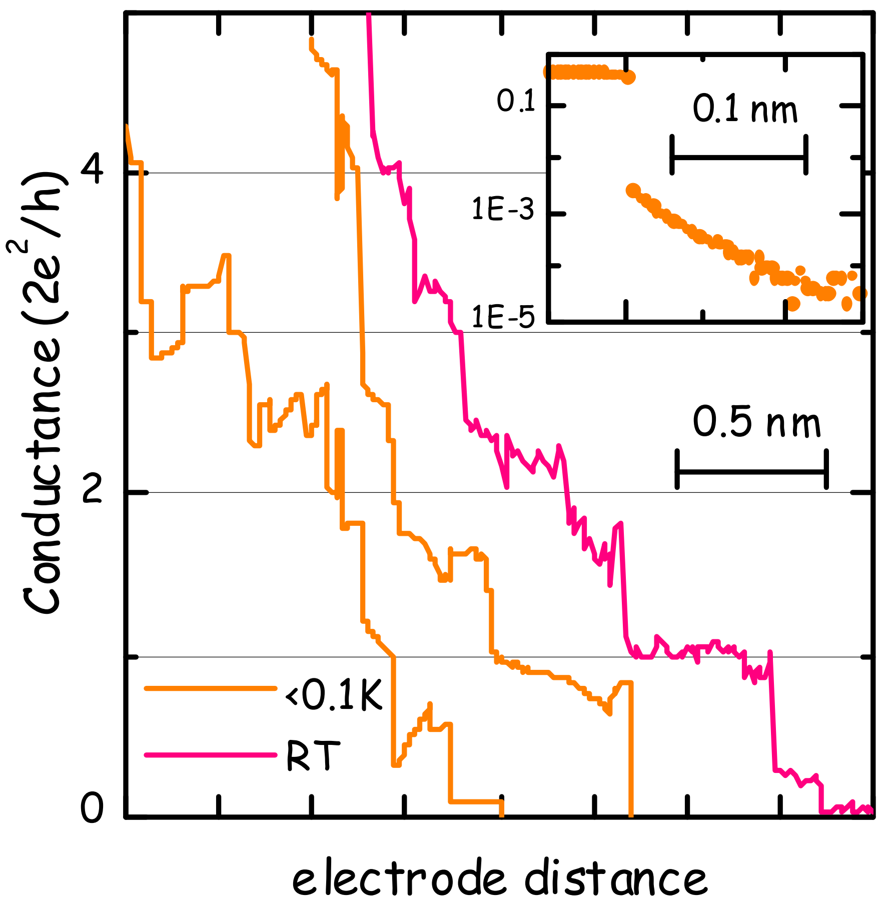
Mechanical adjustment with atomic precision at low temperatures and in UHV

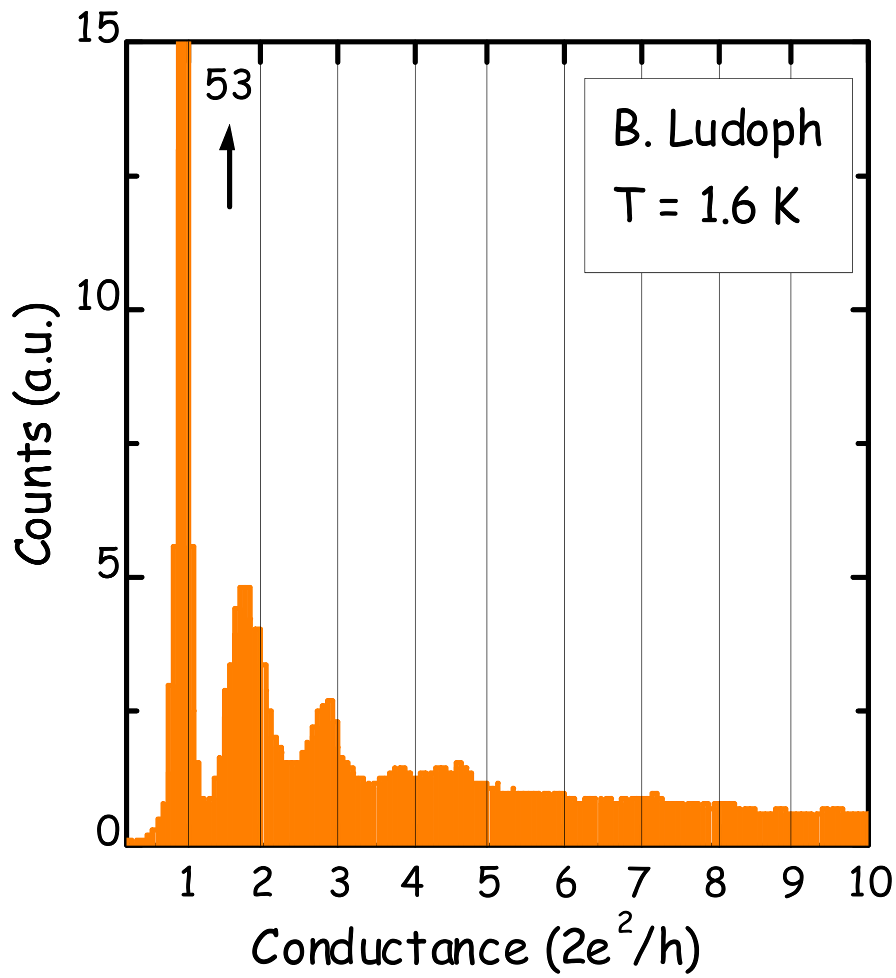
Displacement ratio:
$r = 10^{-4}$ to 10^{-5}

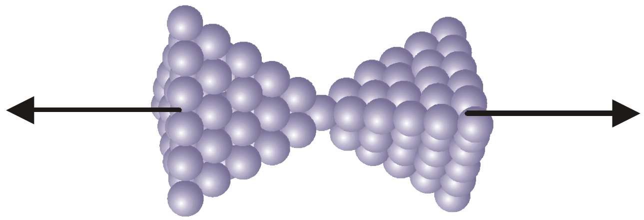
Stability better than 200 fm/h (at 4.2 K)

J.v.Ruitenbeek et al, Rev. Sci. Instrum., 1995

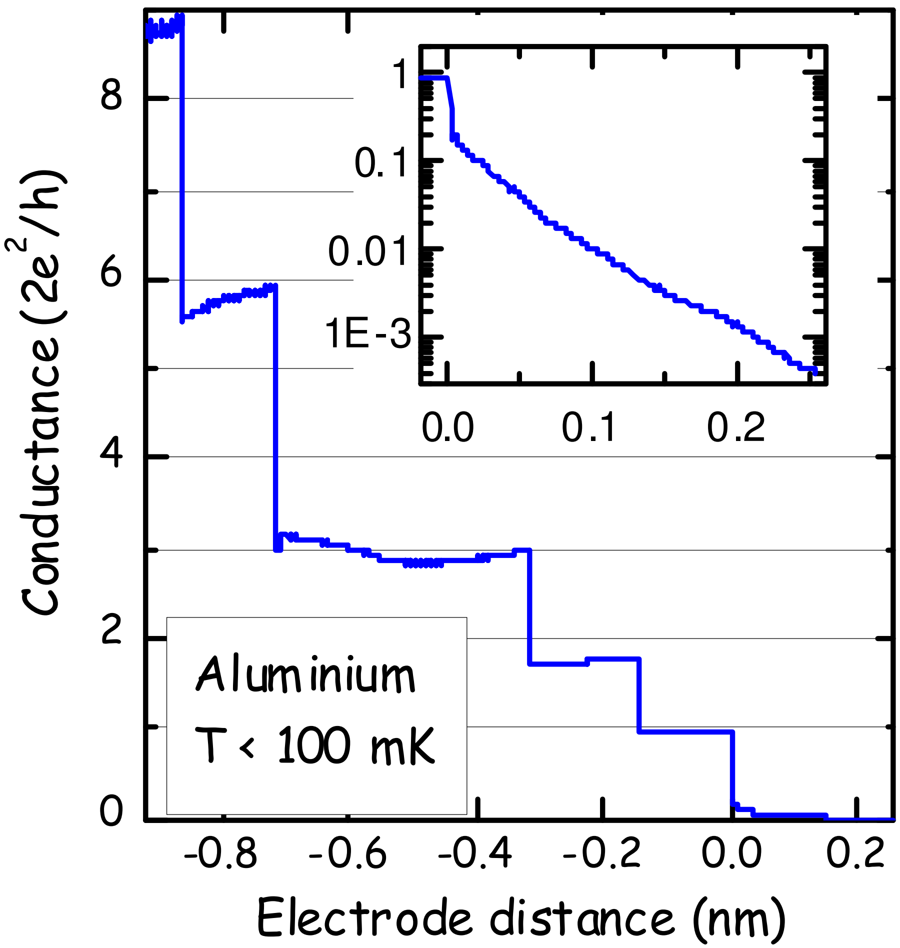
GOLD FEW-ATOMS CONTACTS

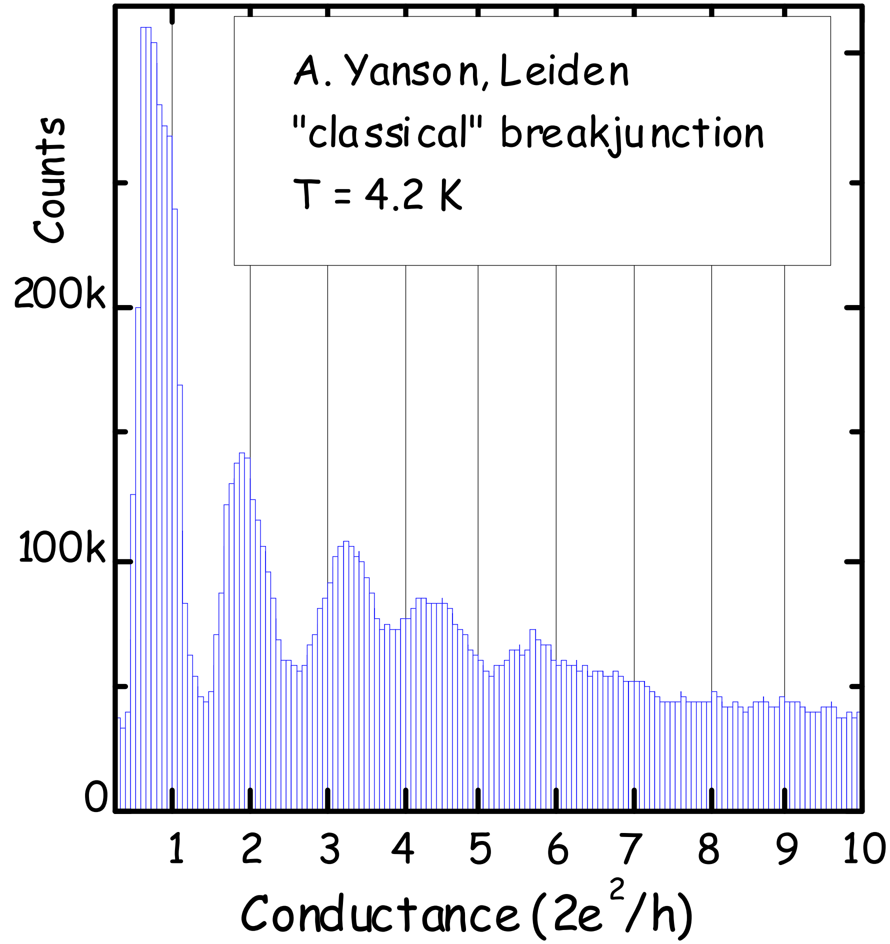






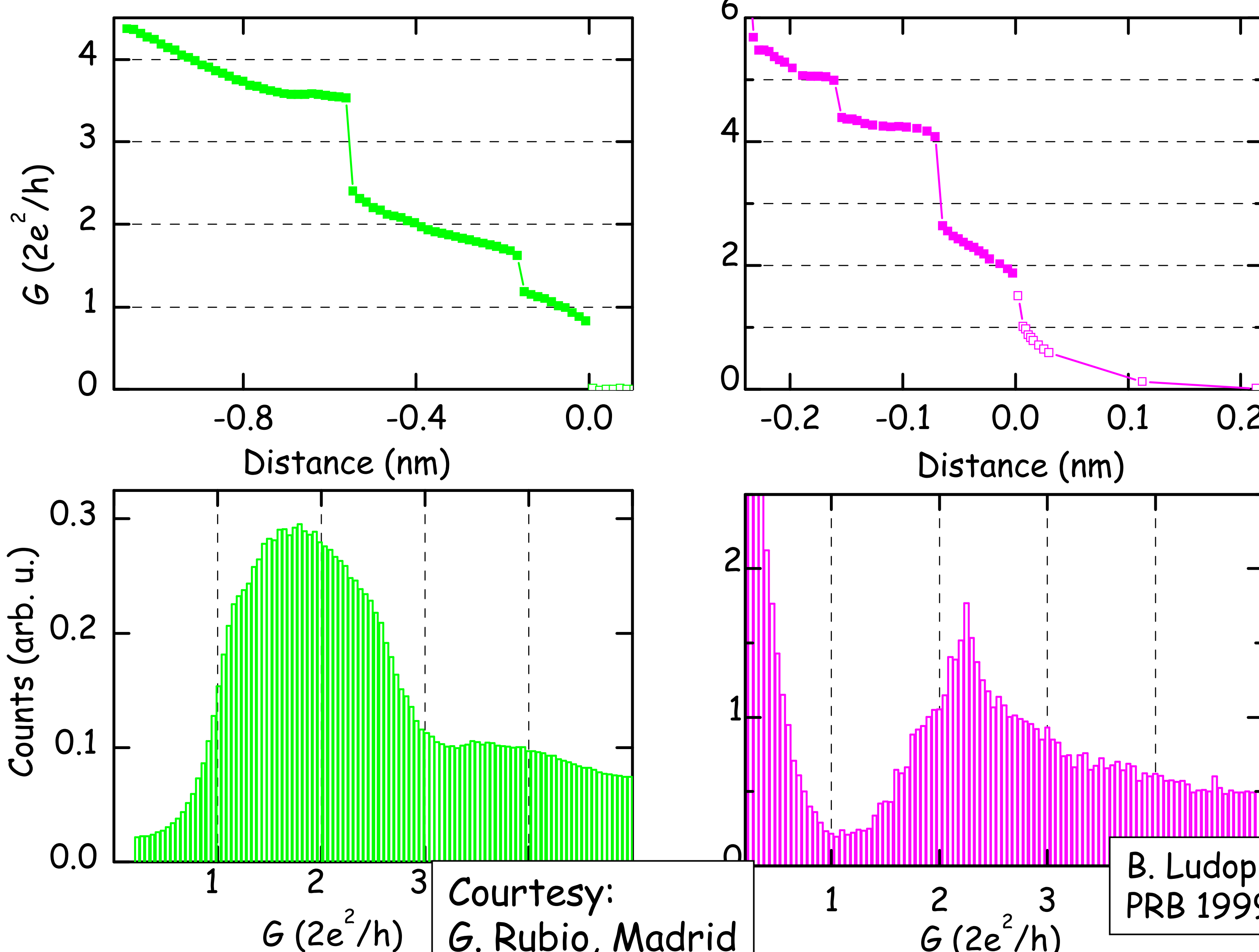
ALUMINUM FEW-ATOMS CONTACTS





Histogram calculated from >6200 scans

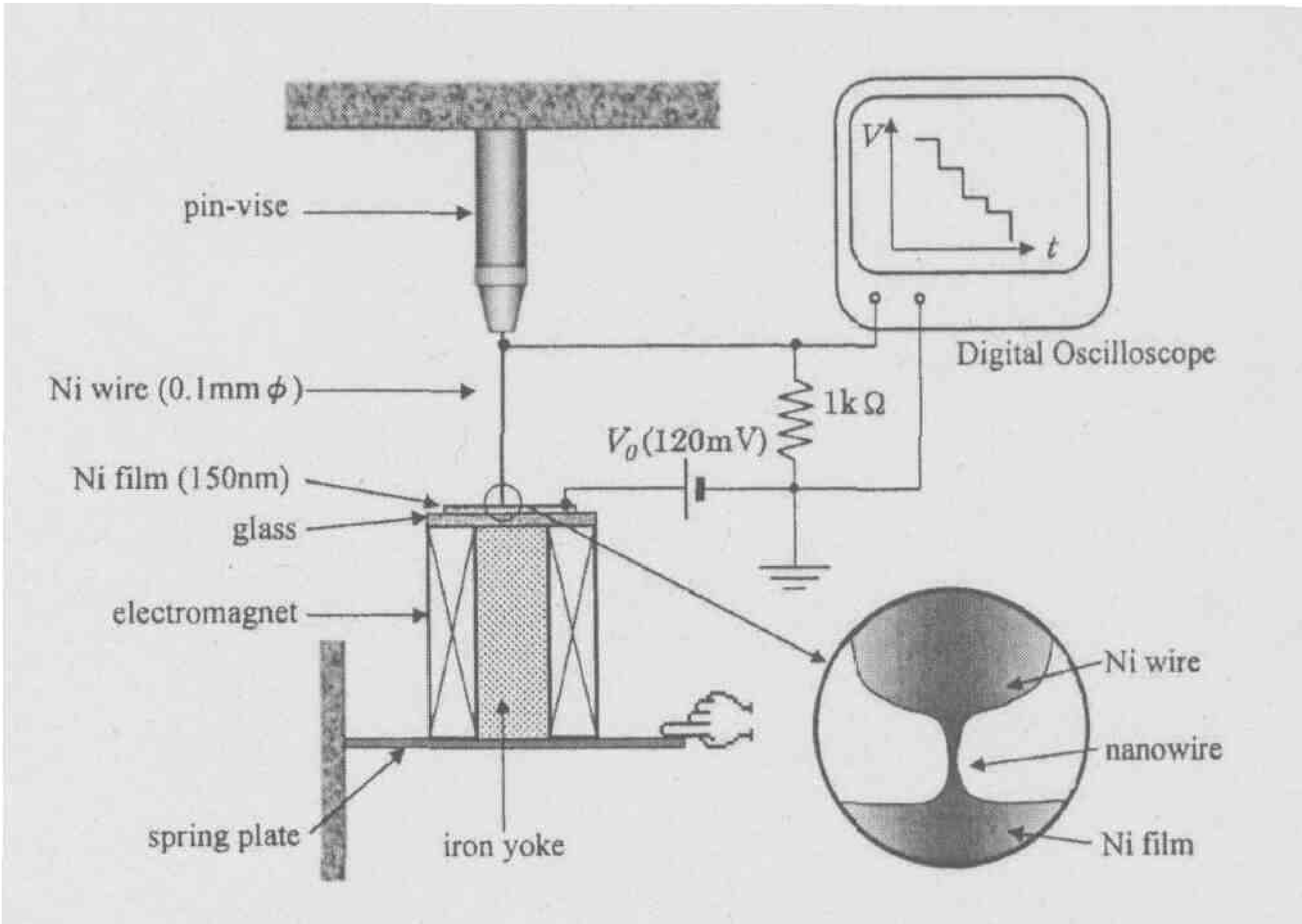
Single-atom contacts of lead and niobium



Courtesy:
G. Rubio, Madrid

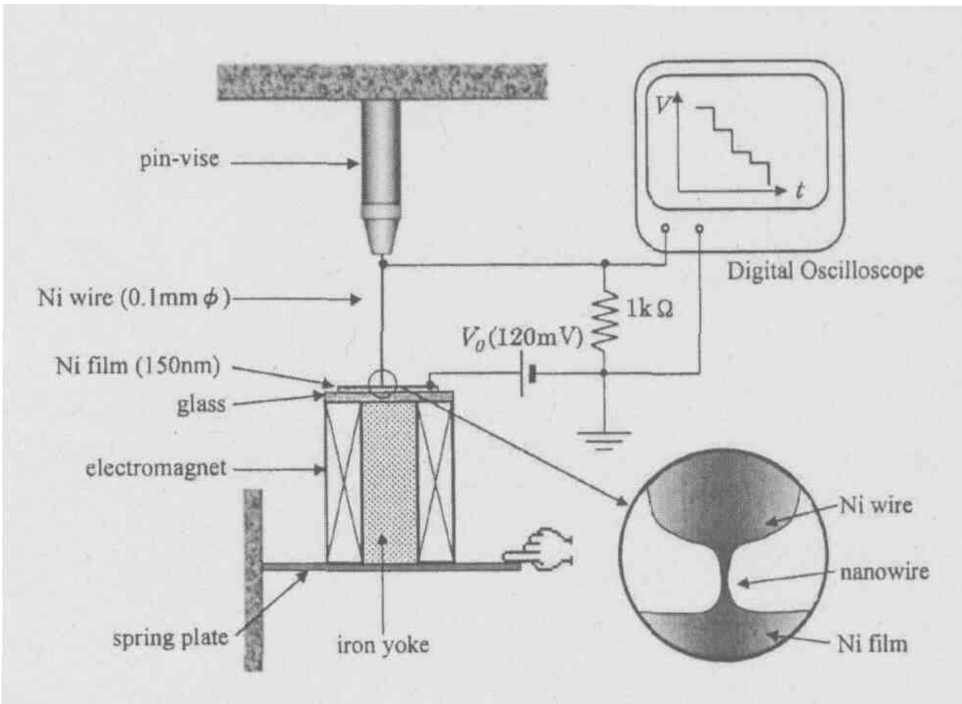
B. Ludoph et al.,
PRB 1999

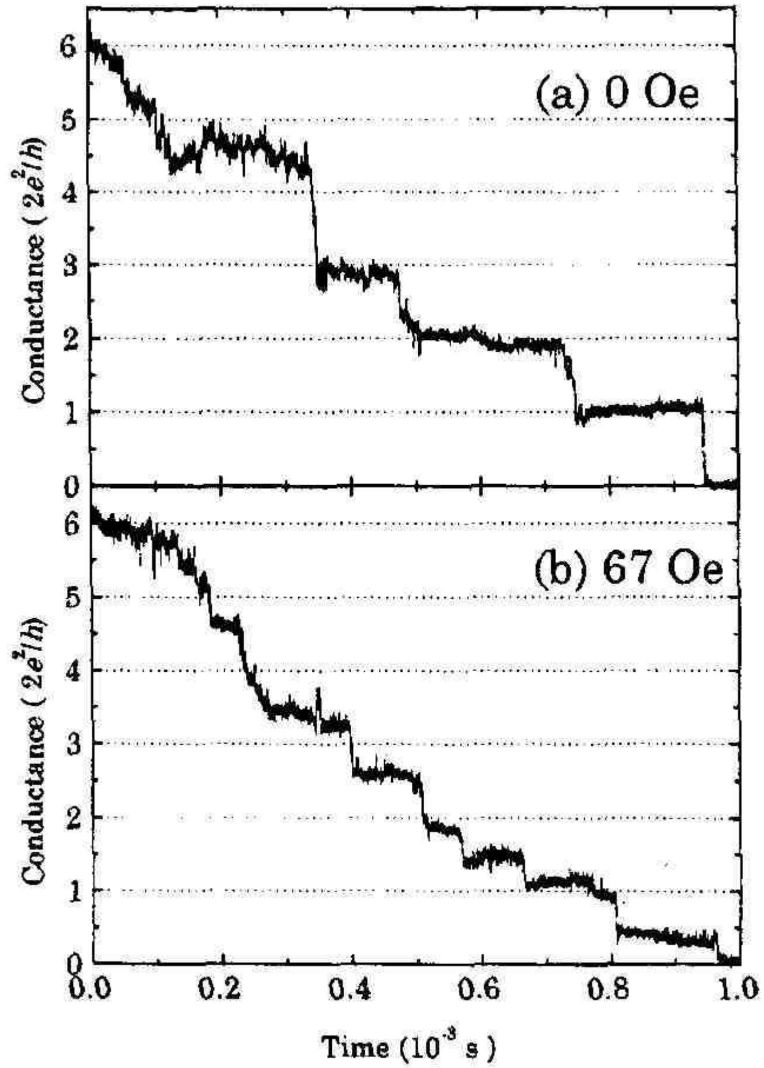
Experiments on ferromagnetic atomic contacts



Ono et al. 1999

Experiments on ferromagnetic atomic contacts





Ono et al. 1999

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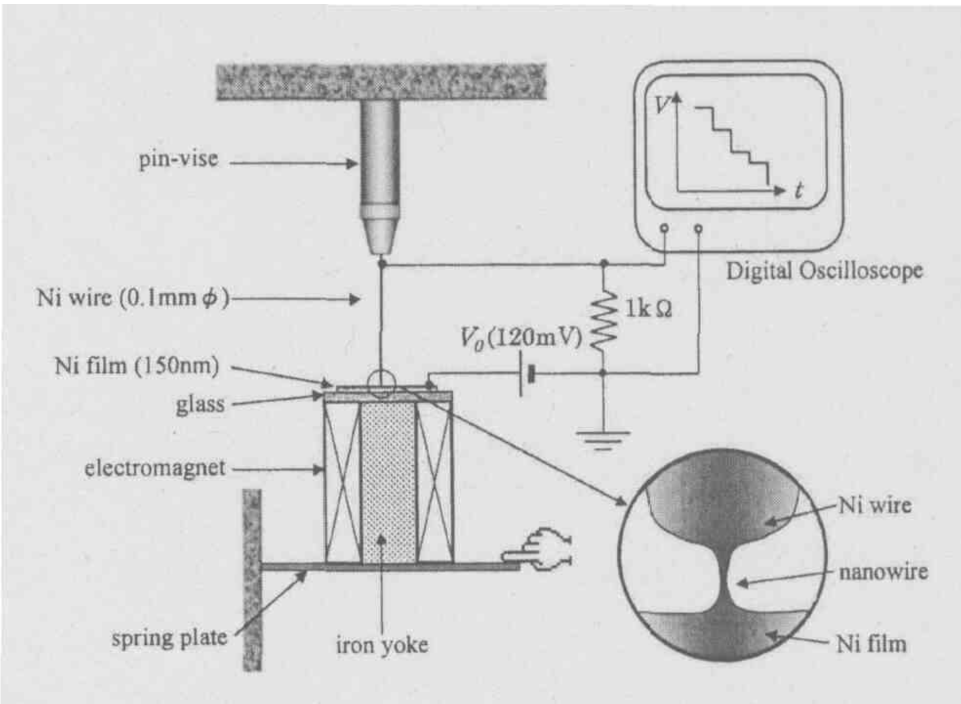
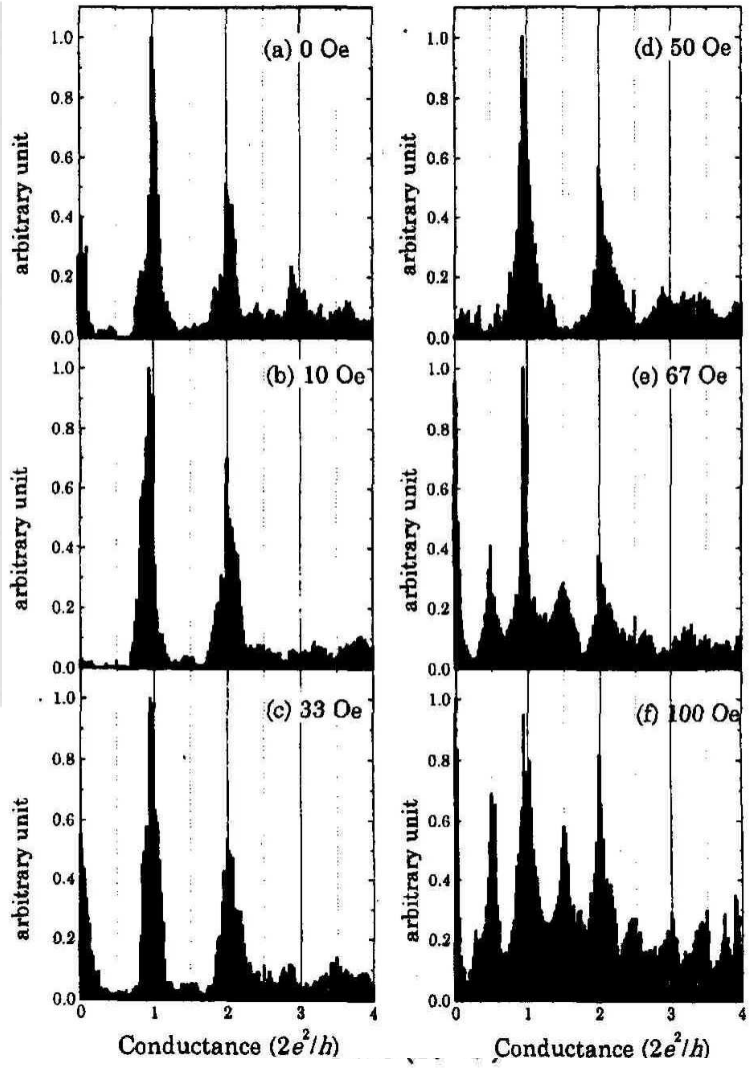
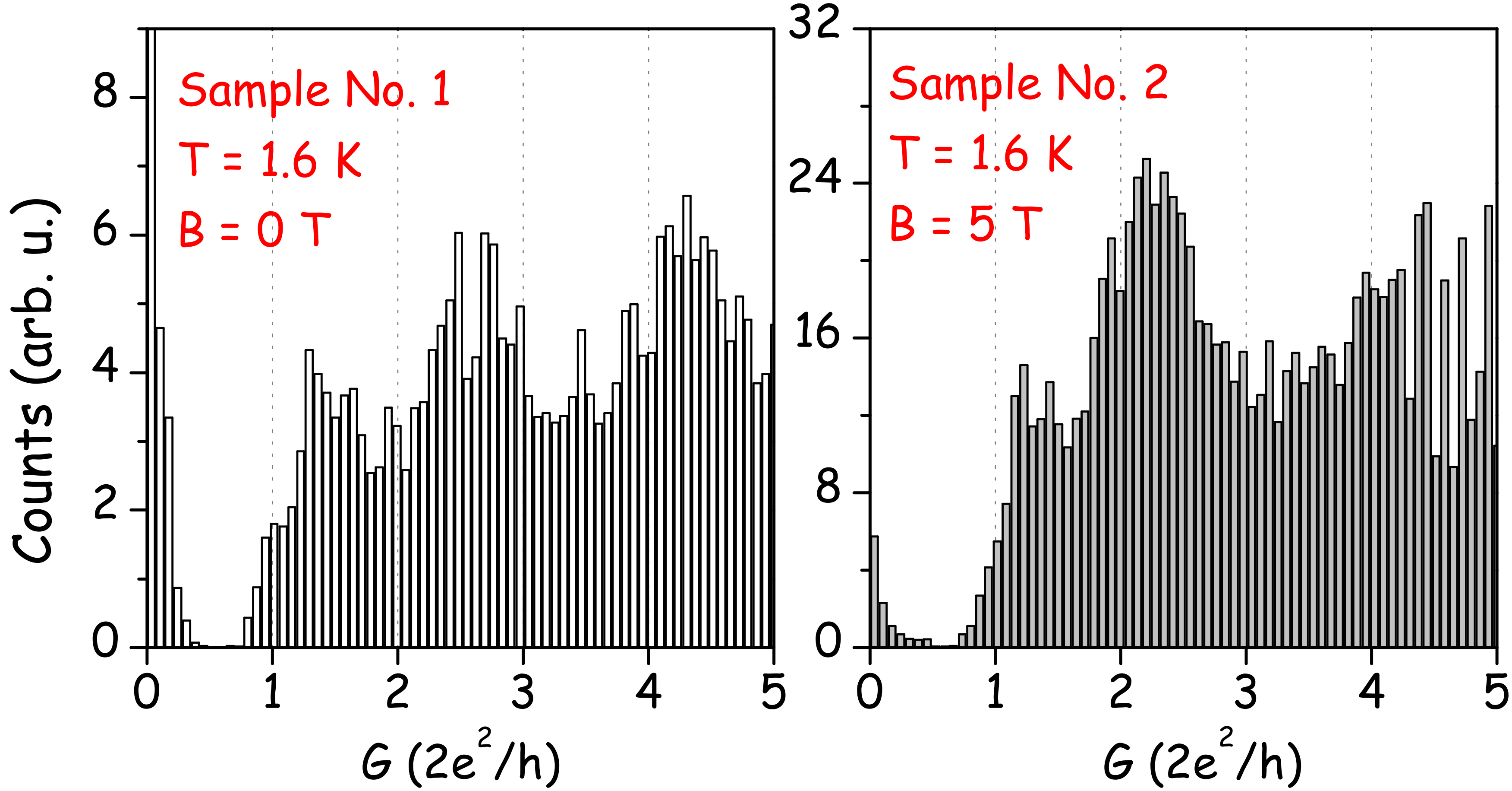




Ono et al. 1999

Histograms of Co few-atoms contacts



R. Arnold et al., in preparation

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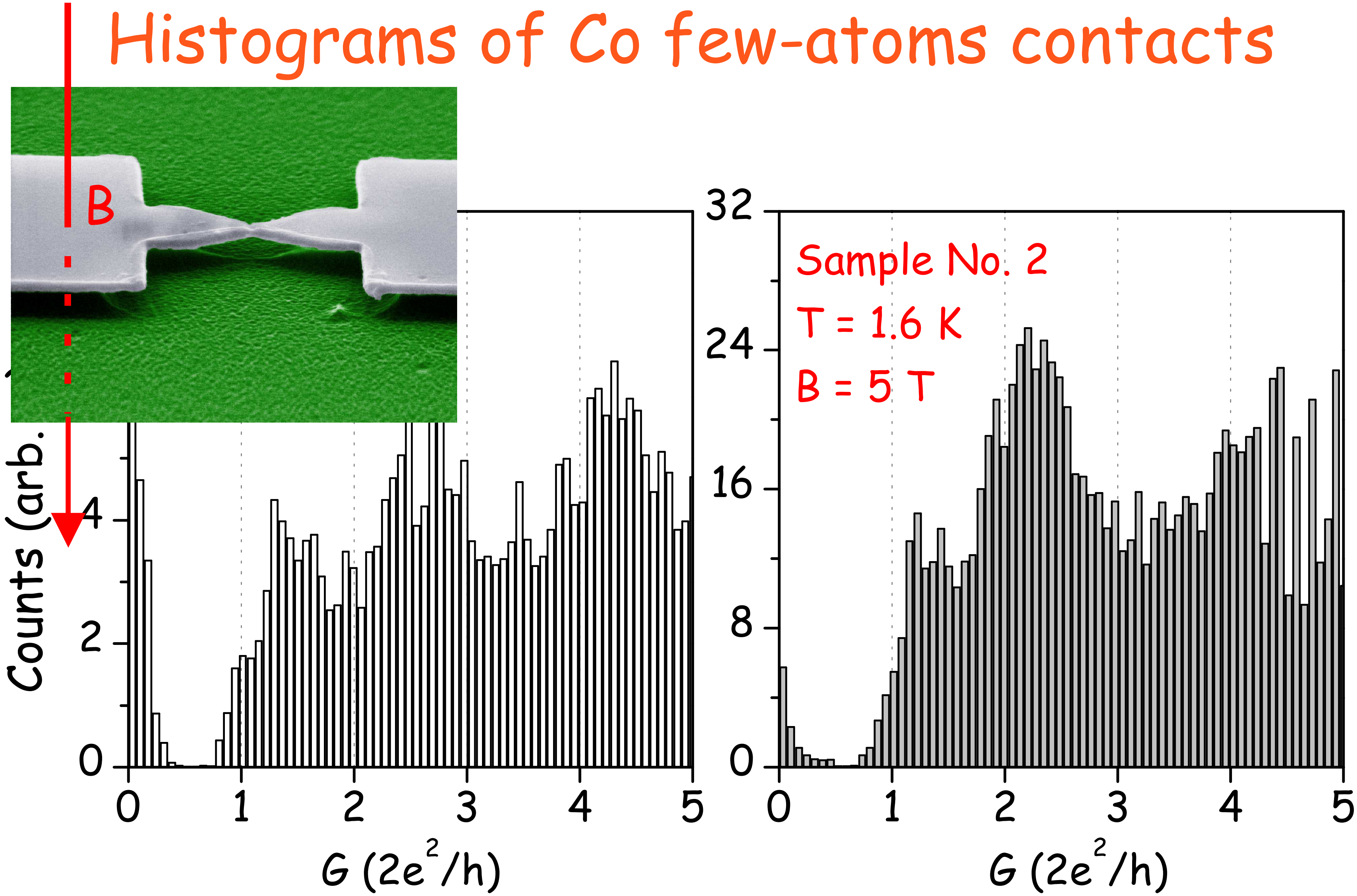

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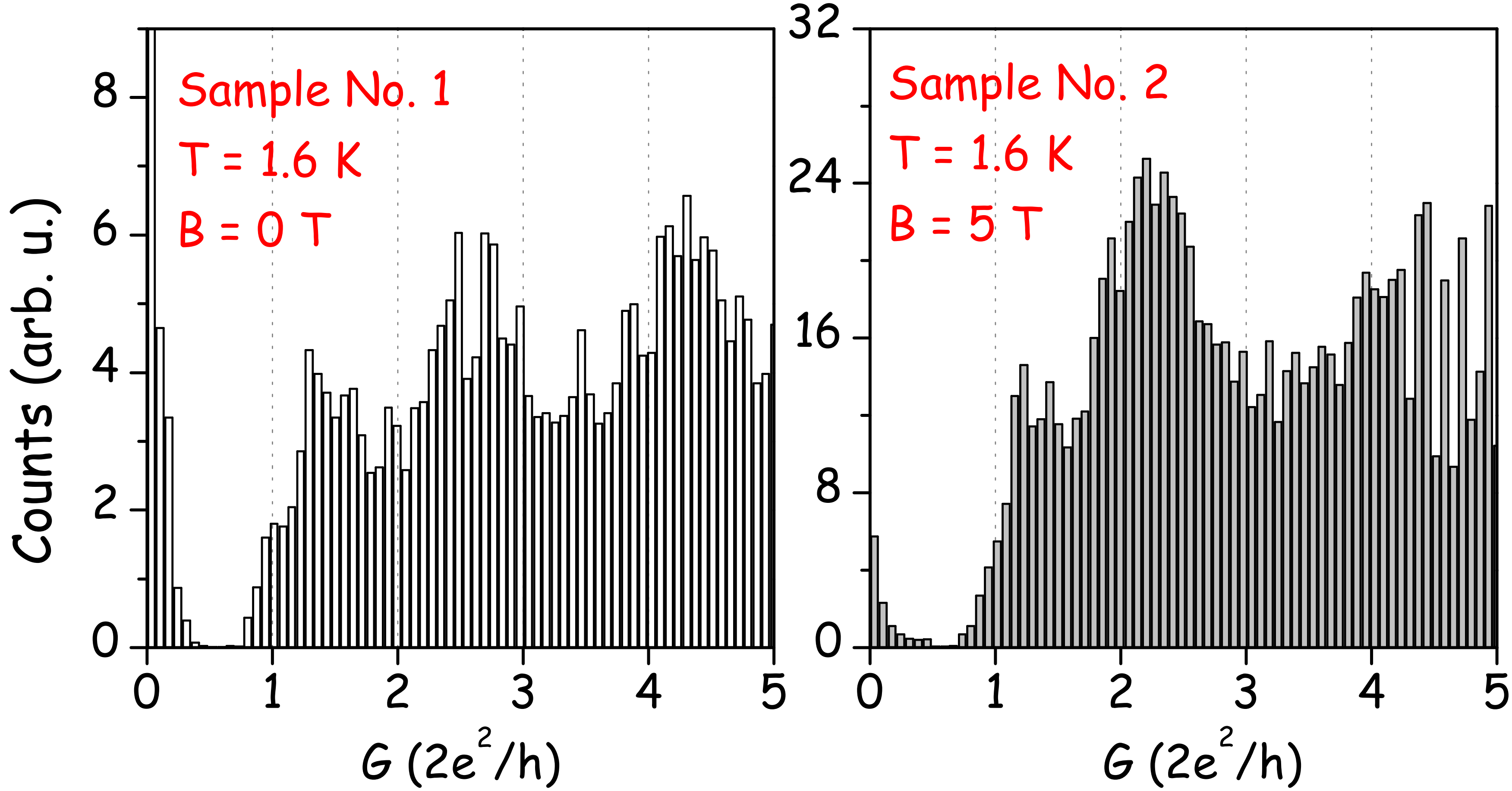
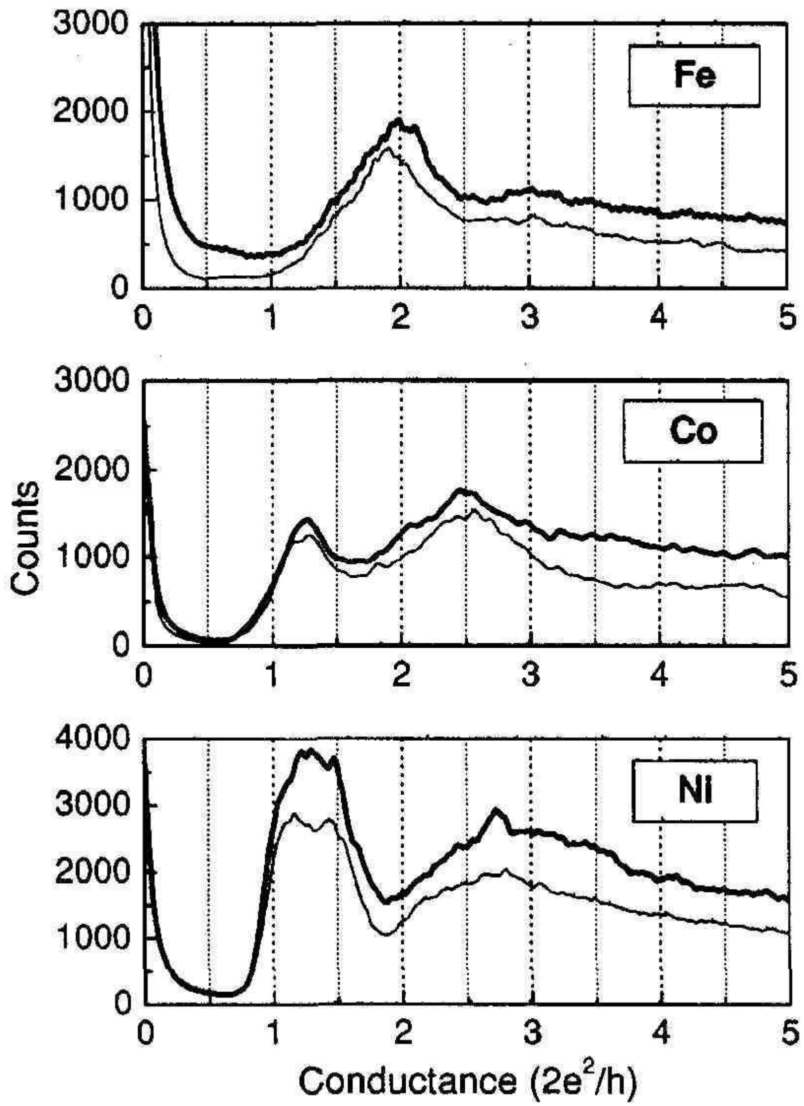
Histograms of Co few-atoms contacts



R. Arnold et al., in preparation

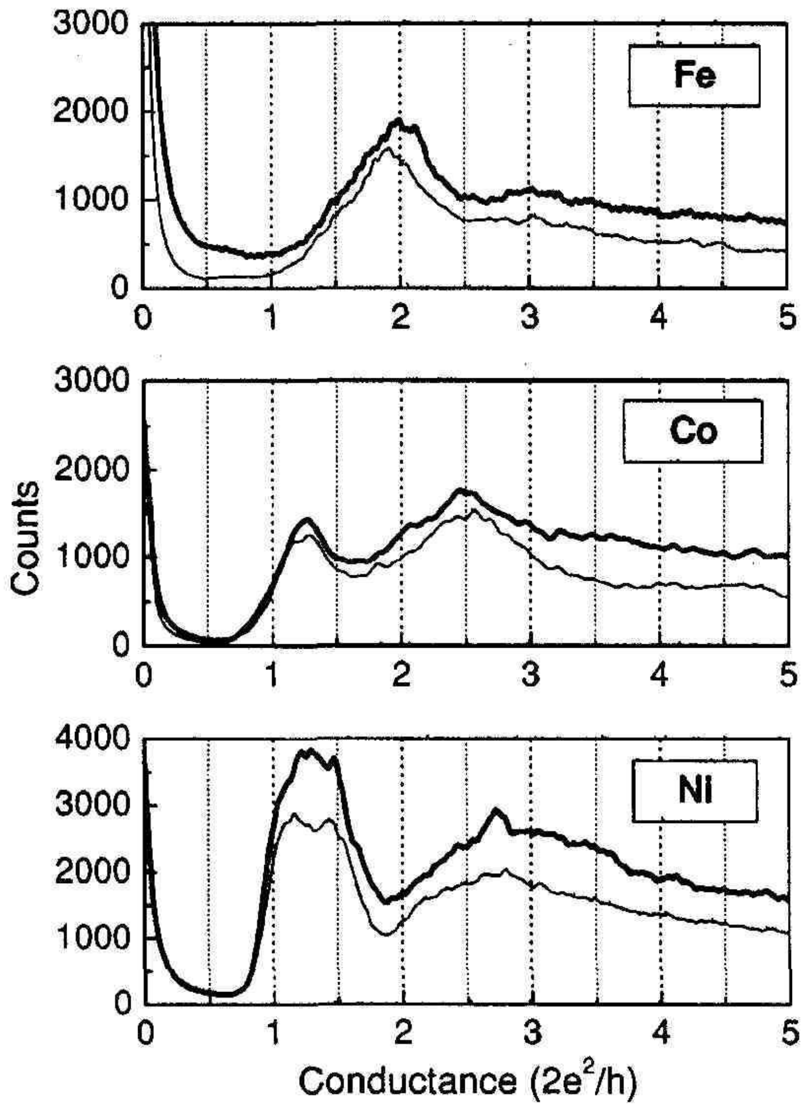
Histograms of „notched-wire“ breakjunctions



Black: B = 5 T
Gray: B = 0T

Untiedt et al. PRB 2004

Histograms of „notched-wire" breakjunctions



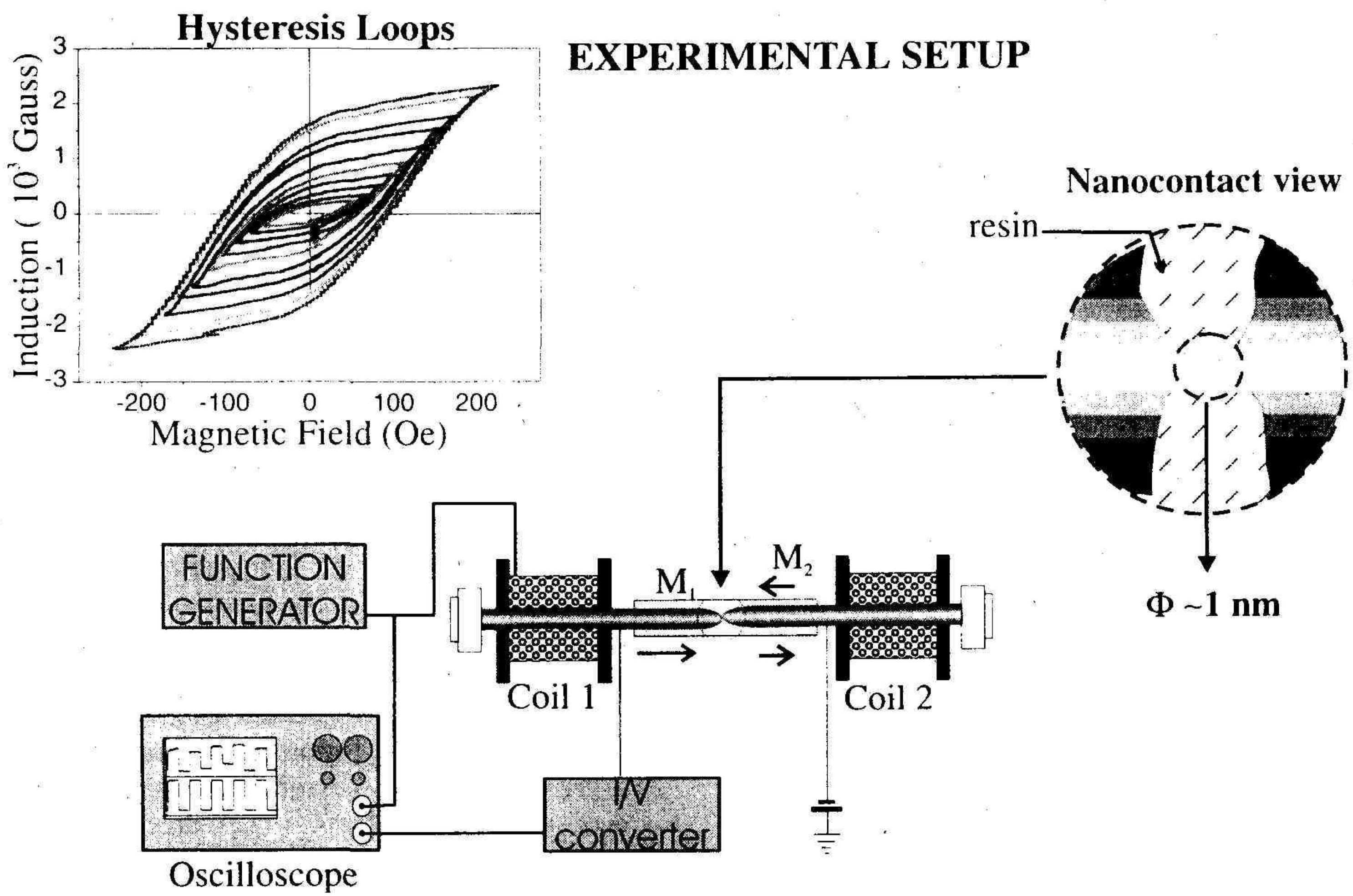
Black: B = 5 T

Gray: B = 0T

No indication of quantization or spin effects on the transport

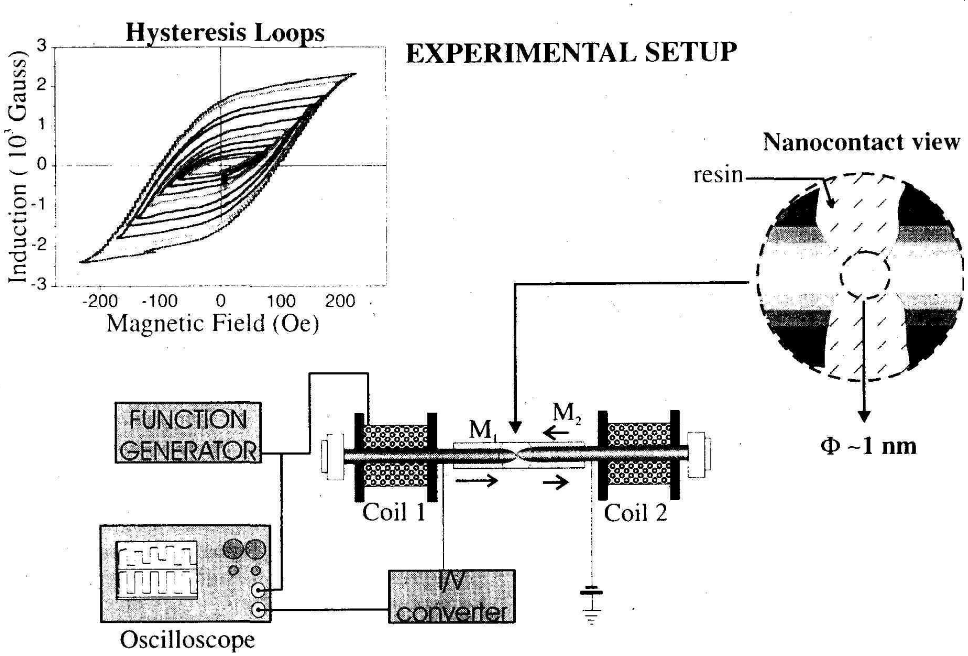
Untiedt et al. PRB 2004

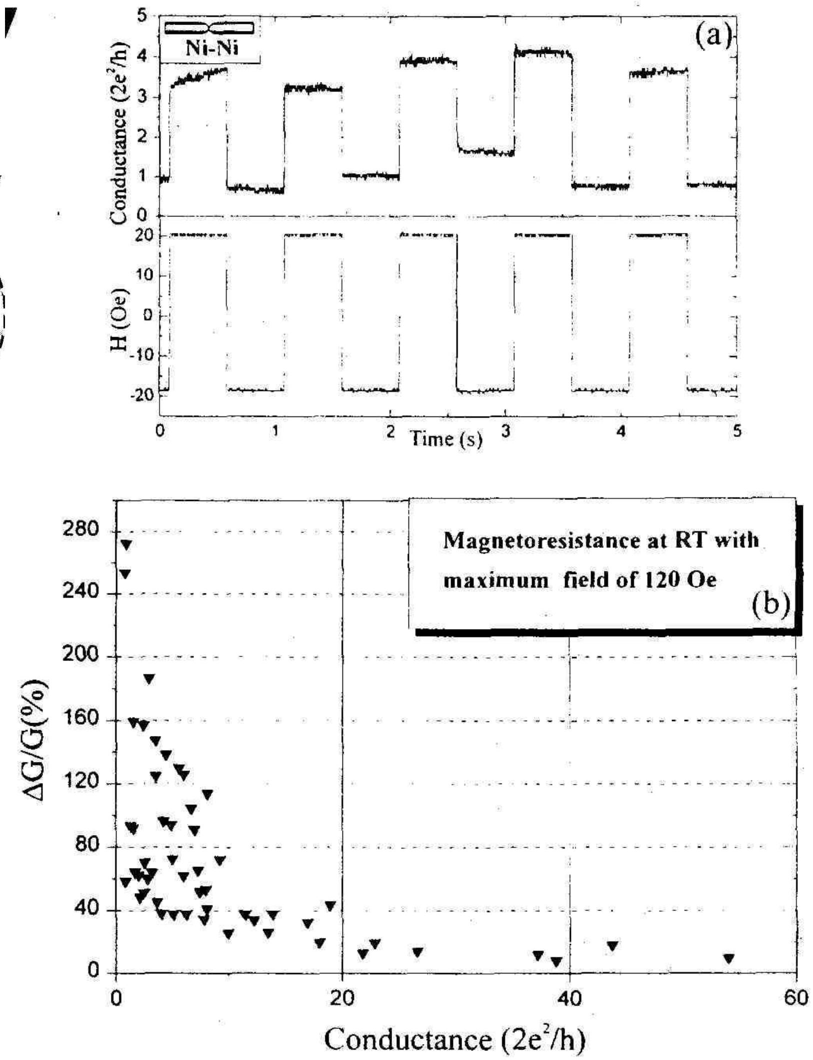
Magnetoresistance of ferromagnetic atomic contacts



Garcia et al., 1999 ff

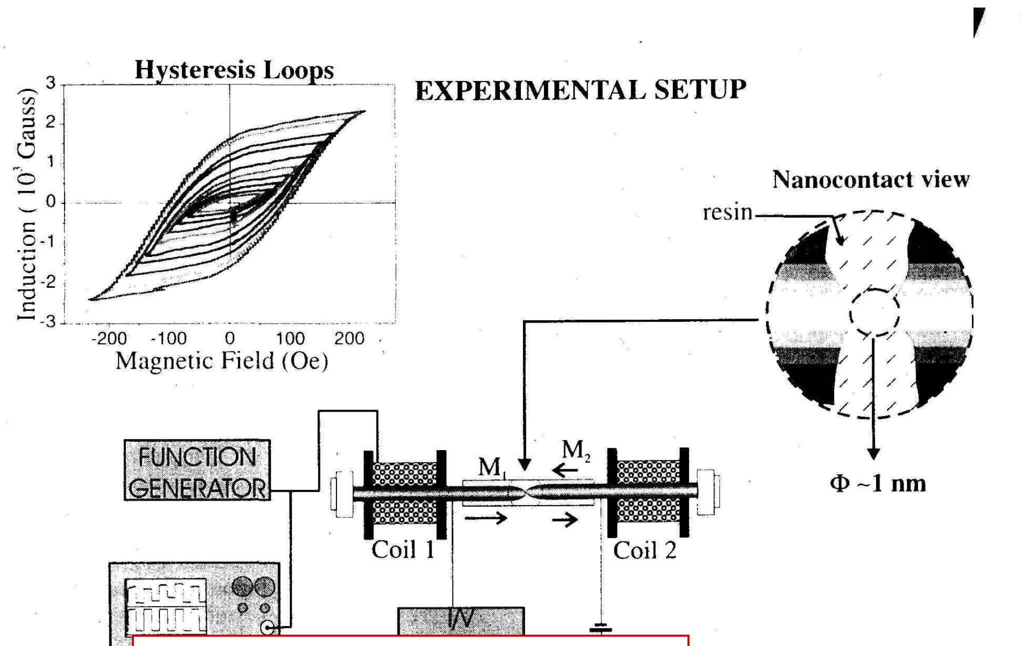
Magnetoresistance of ferromagnetic atomic contacts

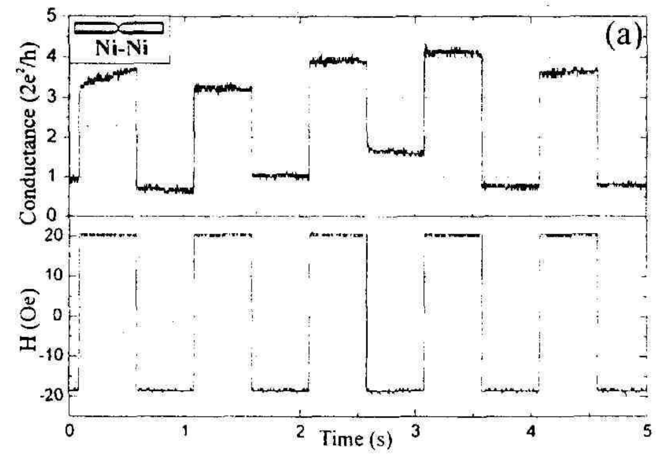


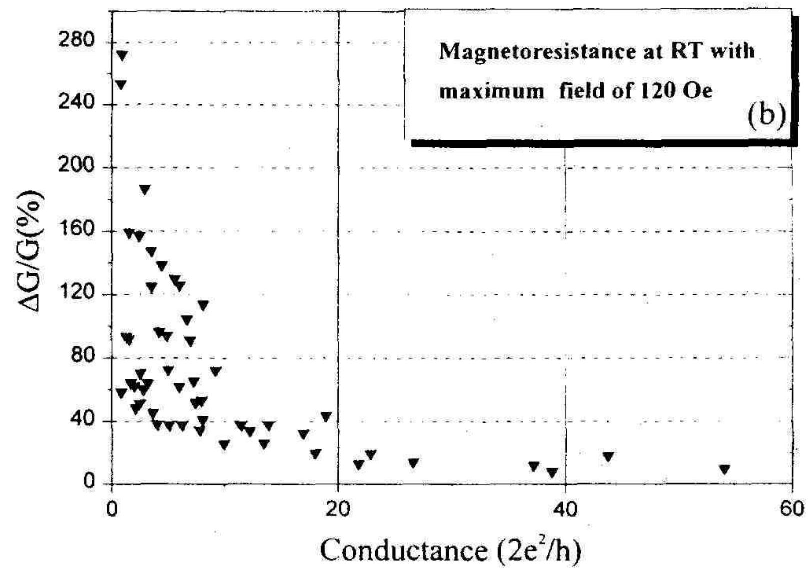


Garcia et al., 1999 ff

Magnetoresistance of ferromagnetic atomic contacts





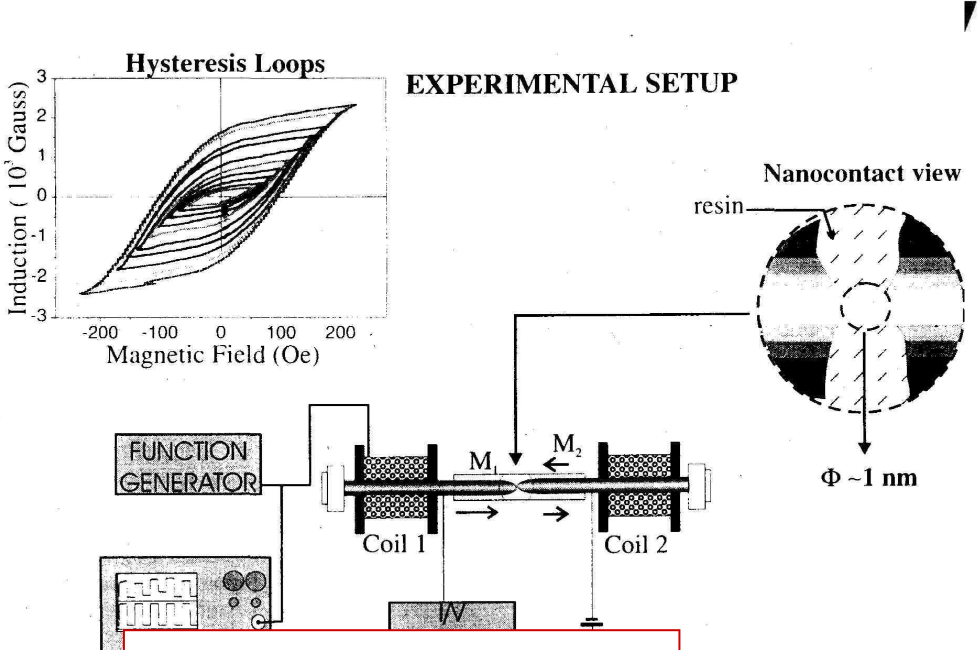


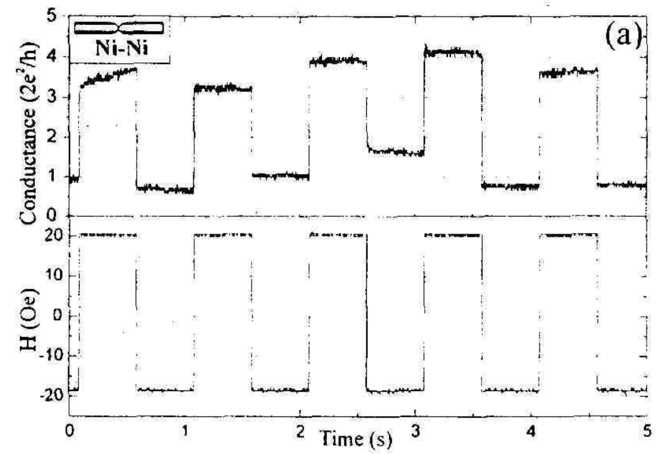
$$MR = \frac{R_{ap} - R_p}{R_p}$$

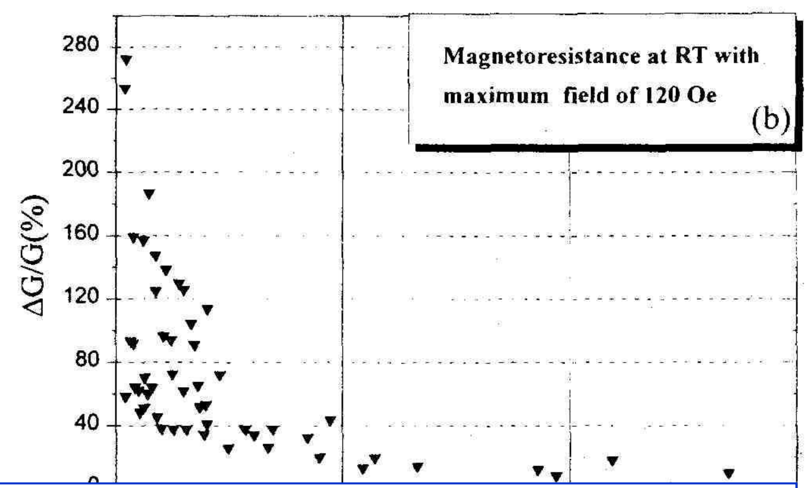
BMR up to 700%

Garcia et al., 1999 ff

Magnetoresistance of ferromagnetic atomic contacts







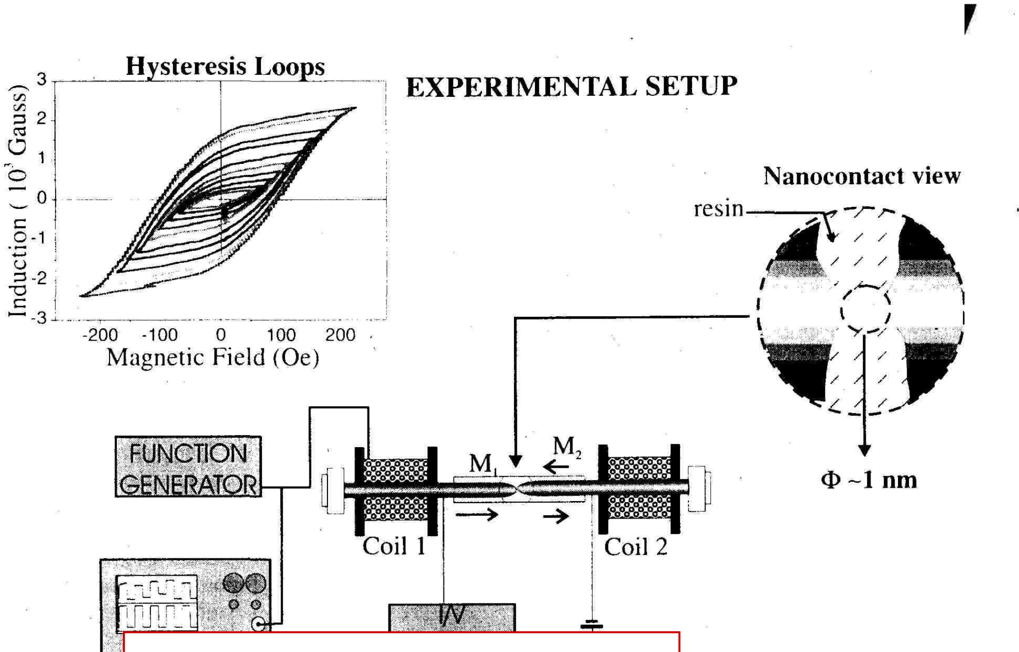
$$MR = \frac{R_{ap} - R_p}{R_p}$$

BMR up to 700%

Garcia et al., 1999 ff

Theory: Tatara et al., PRL 1999 (DWs)
Falloon et al., PRB 2004 (spin blocking)

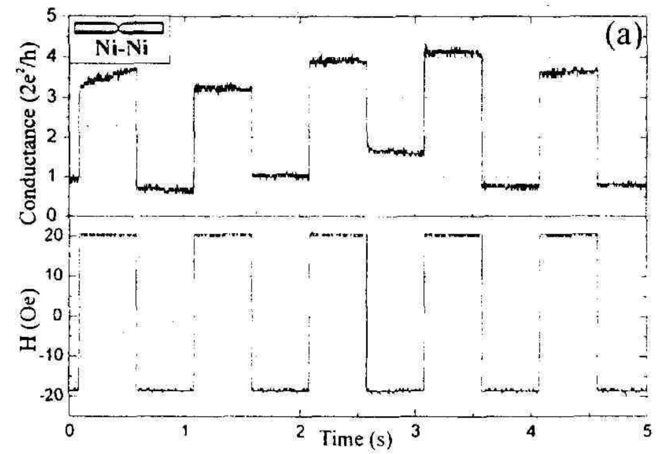
Magnetoresistance of ferromagnetic atomic contacts

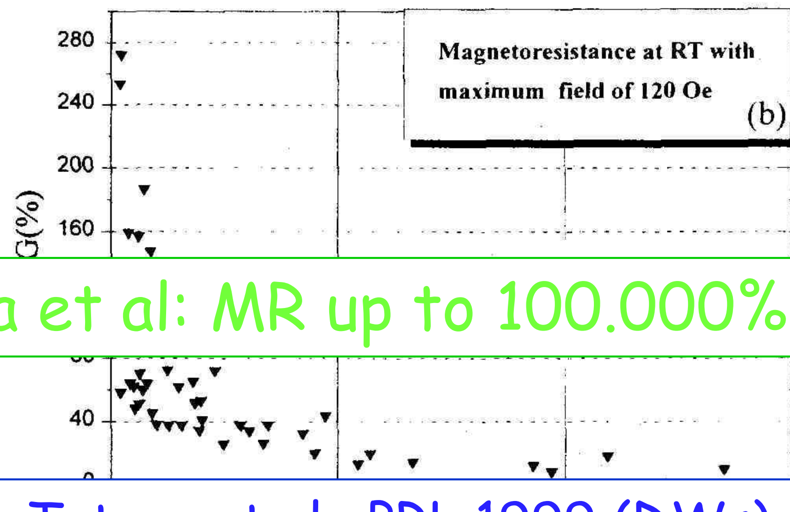


$$MR = \frac{R_{ap} - R_p}{R_p}$$

BMR up to 700%

Garcia et al., 1999 ff

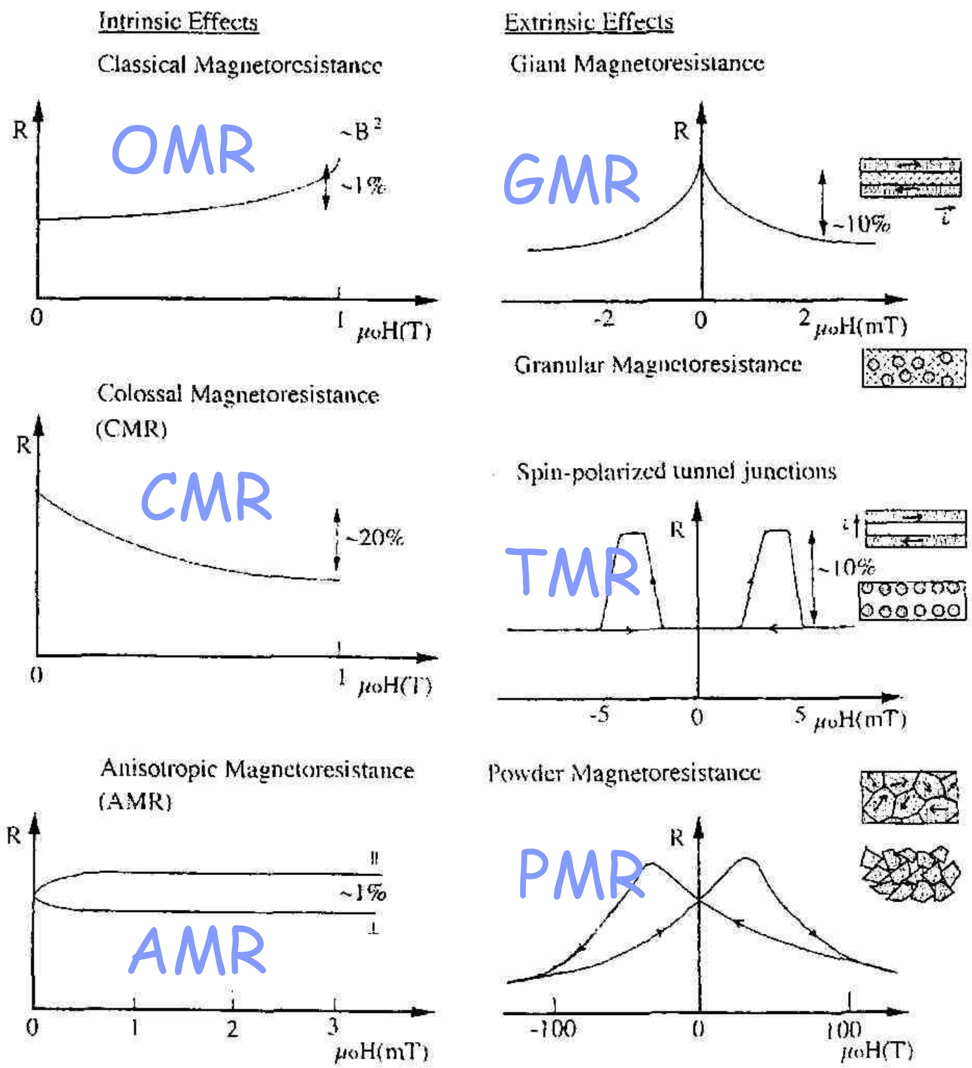




Chopra et al: MR up to 100.000%

Theory: Tatara et al., PRL 1999 (DWs)
Falloon et al., PRB 2004 (spin blocking)

Origin of strong MR?



Coey et al., APL 99

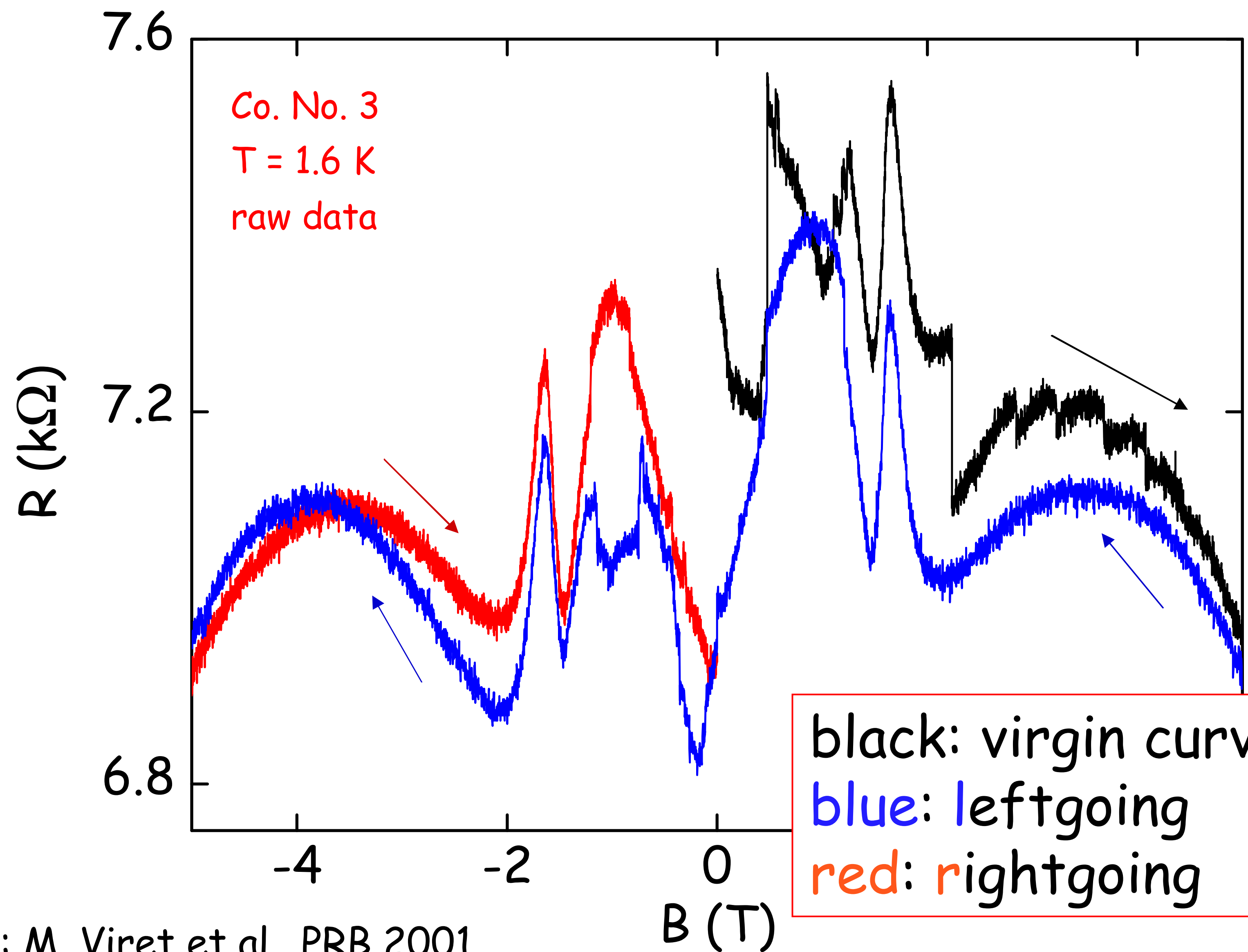
Other possibilites:

BMR: Ballistic Magnetoresistance

Assumption: quantized channel transmissions

Magnetoresistance of lithographic breakjunctions in perpendicular field

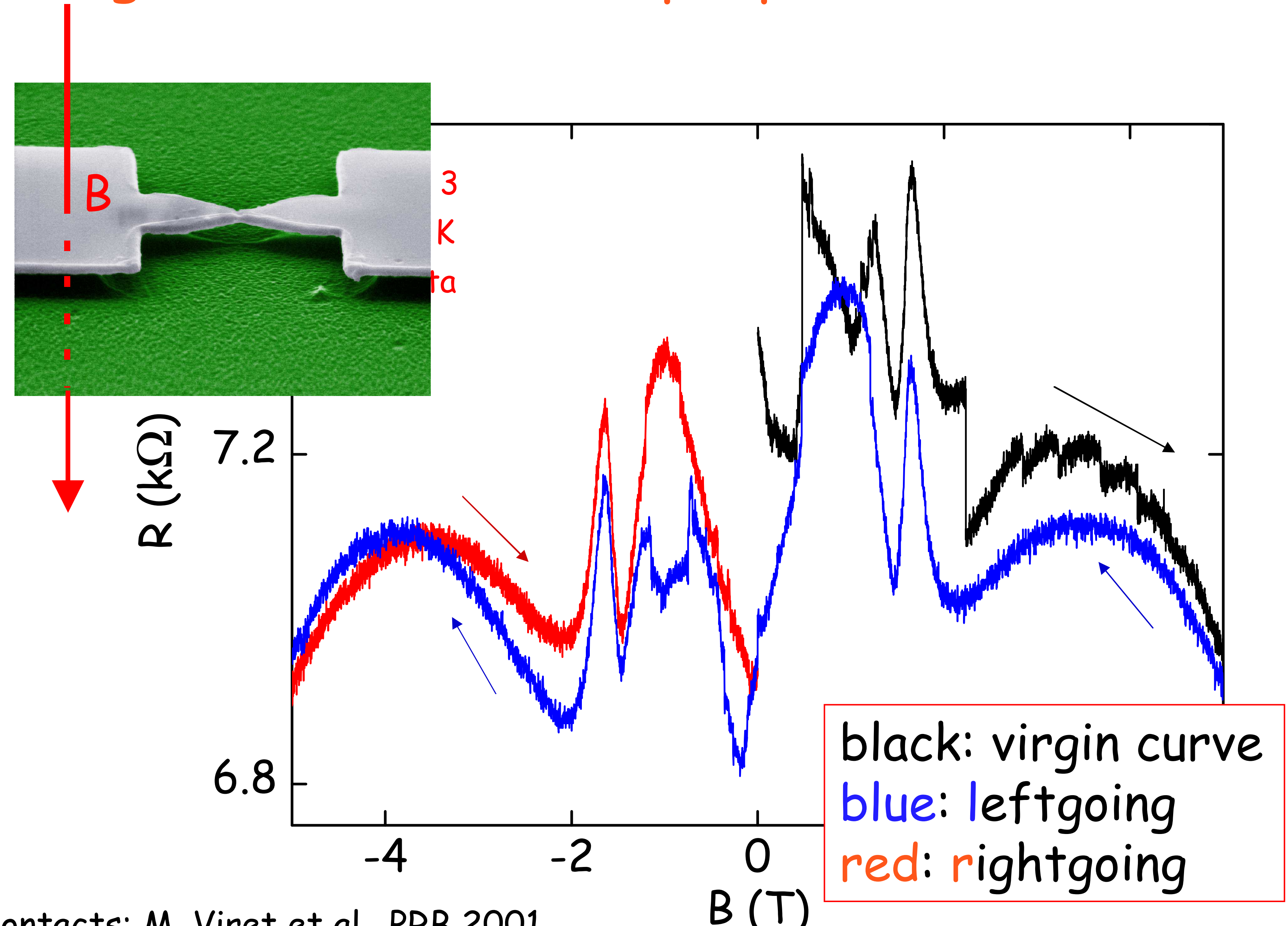
Magnetoresistance in perpendicular field



black: virgin curve
blue: leftgoing
red: rightgoing

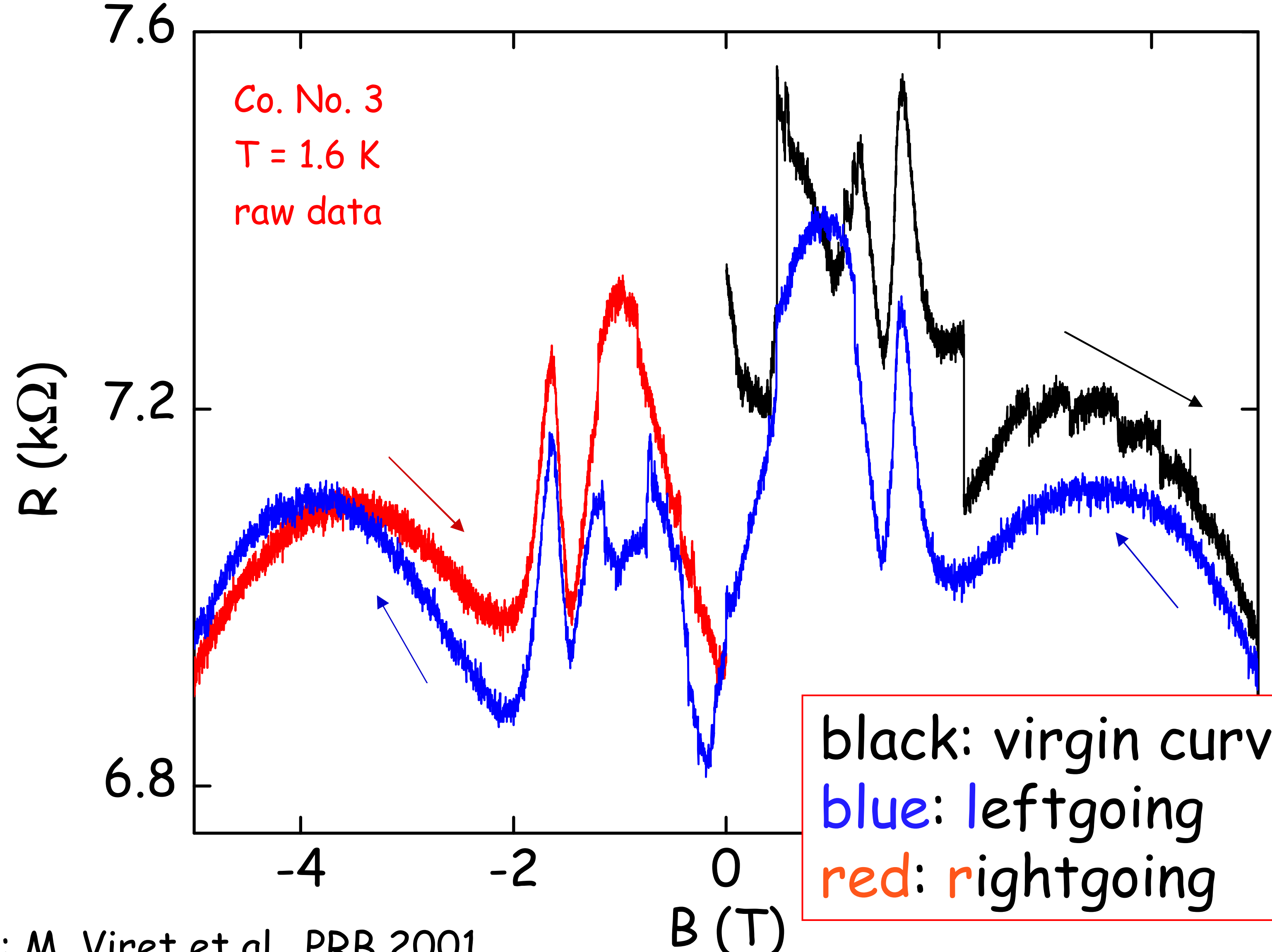
Ni contacts: M. Viret et al., PRB 2001

Magnetoresistance in perpendicular field



Ni contacts: M. Viret et al., PRB 2001

Magnetoresistance in perpendicular field



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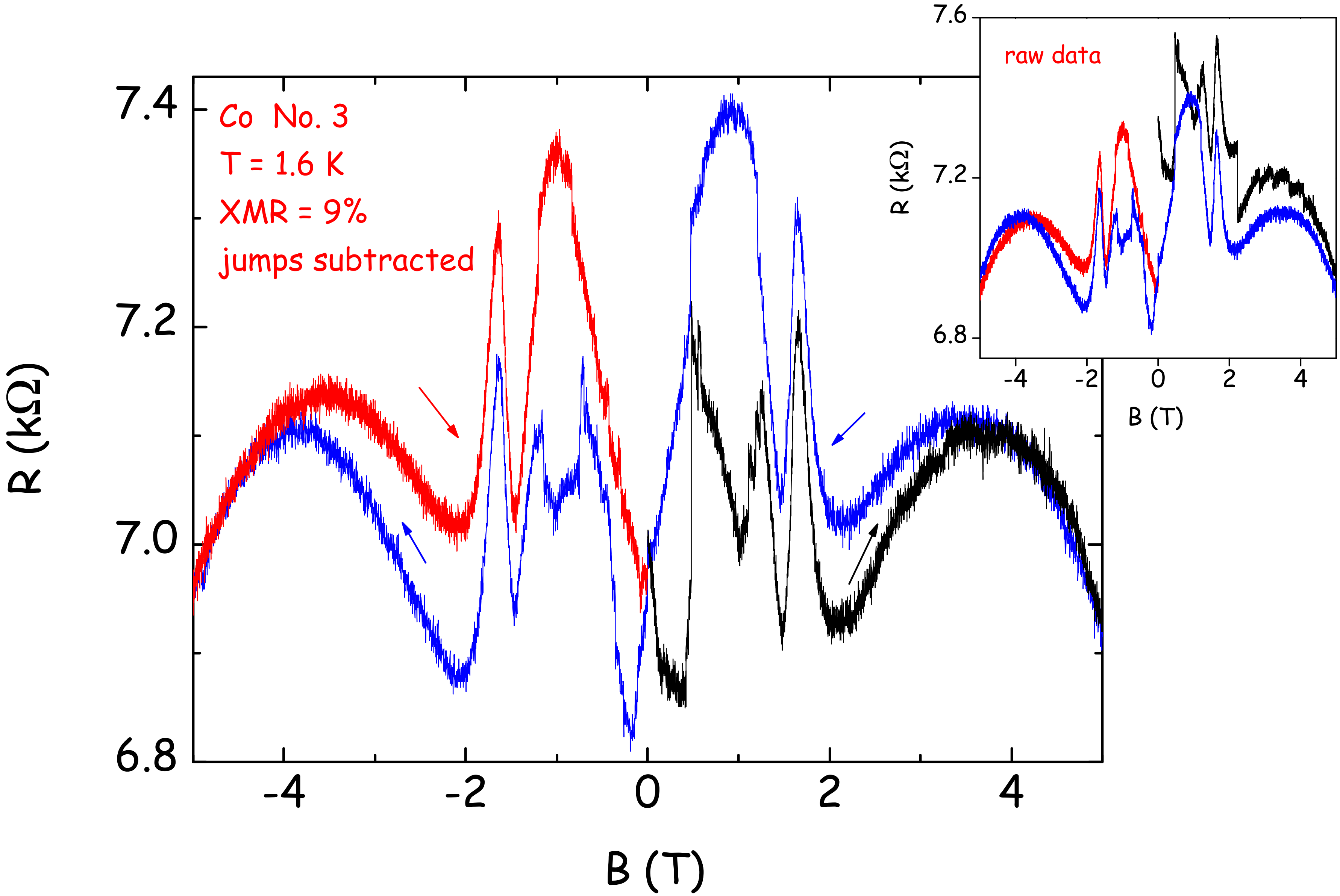
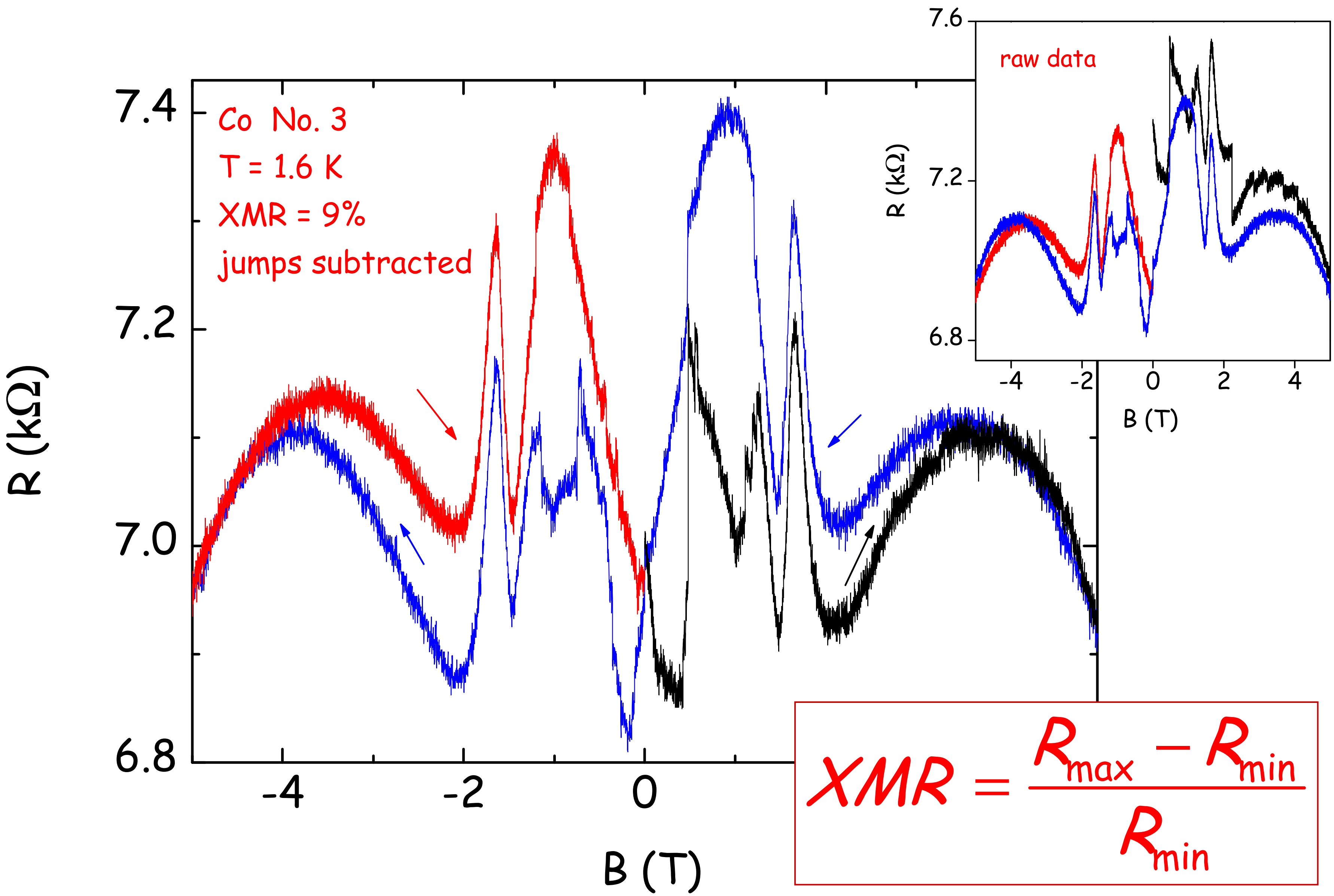
Magnetoresistance in perpendicular field

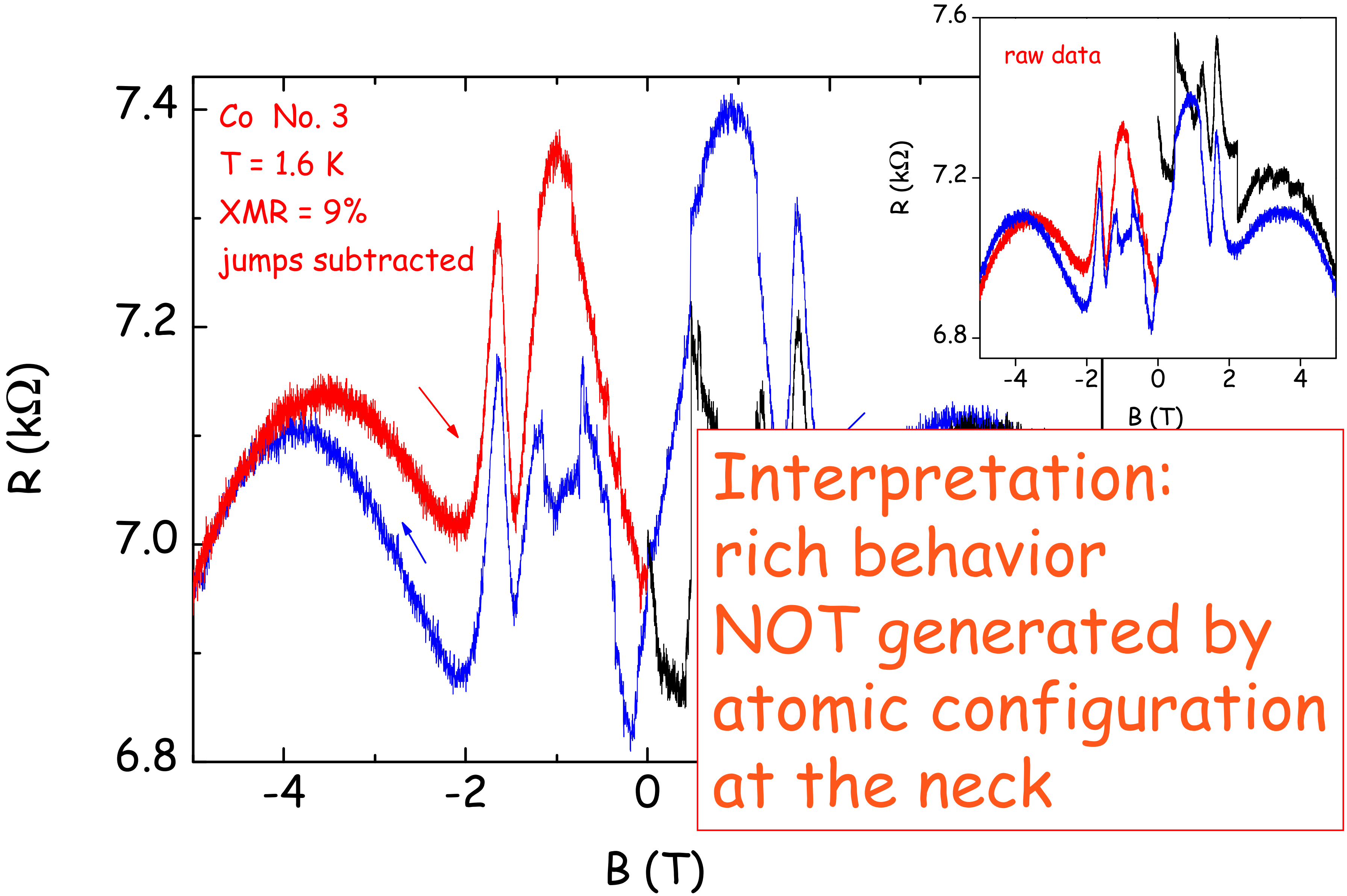


Magnetoresistance in perpendicular field



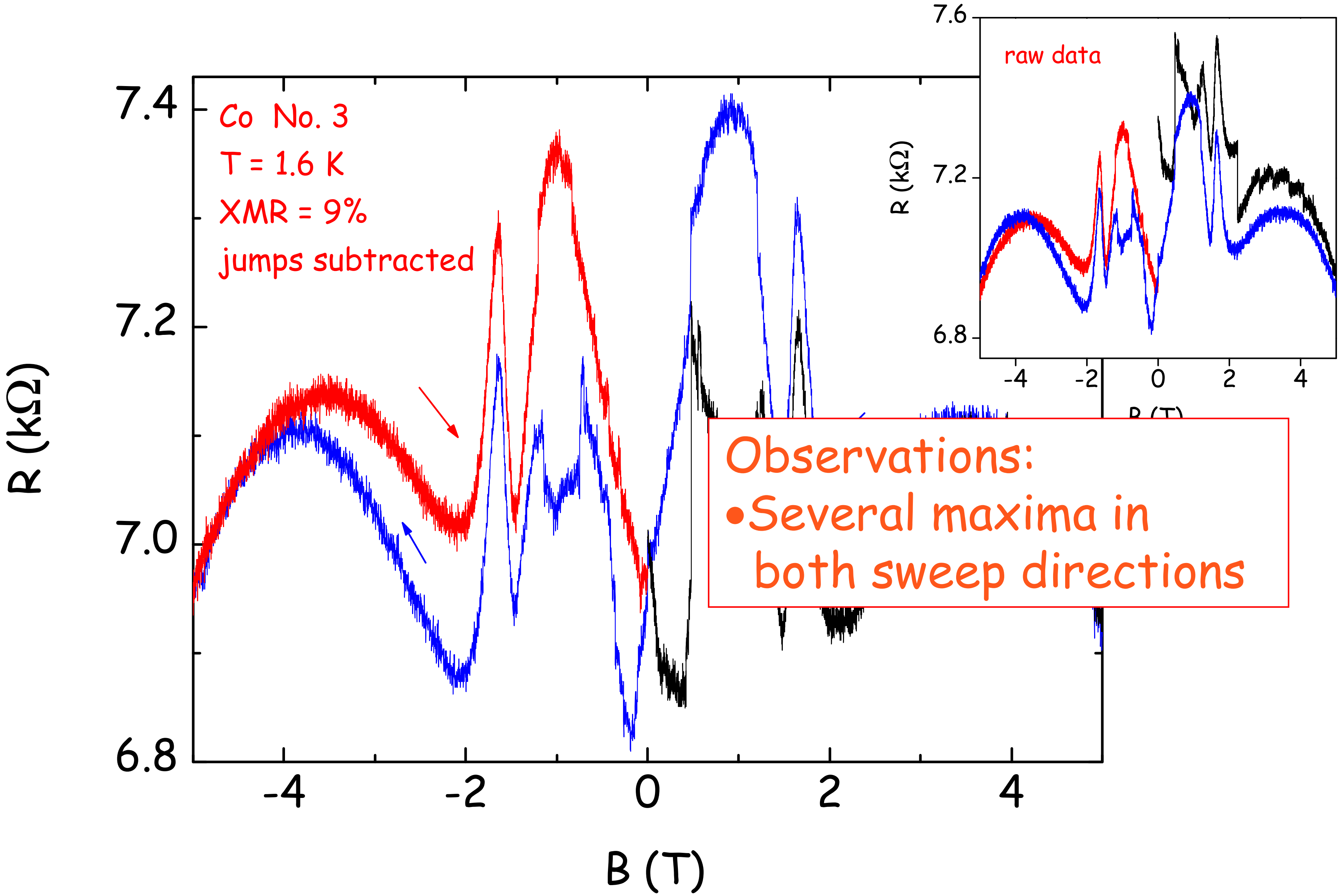
$$XMR = \frac{R_{max} - R_{min}}{R_{min}}$$

Magnetoresistance in perpendicular field



Interpretation:
rich behavior
NOT generated by
atomic configuration
at the neck

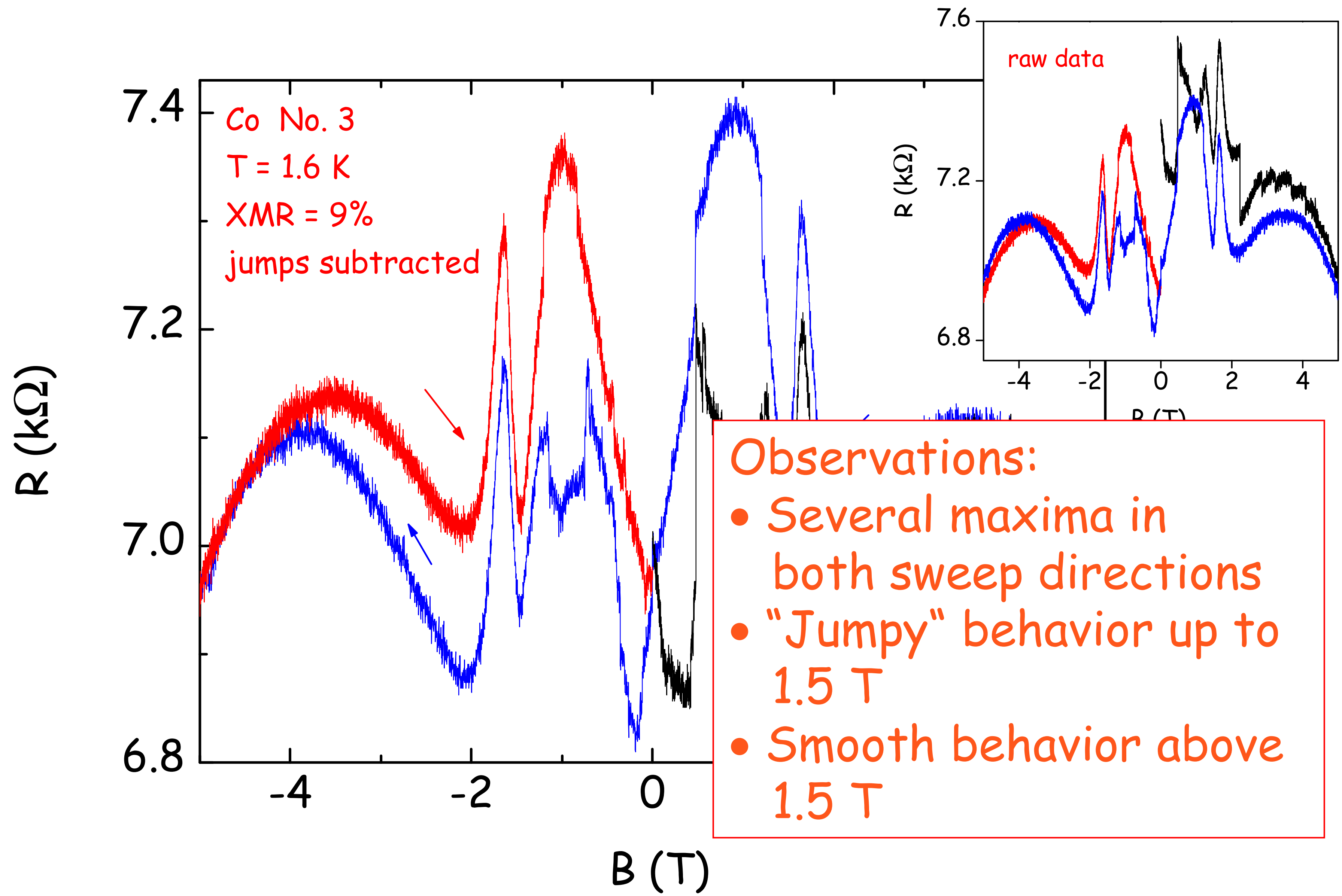
Magnetoresistance in perpendicular field



Observations:

- Several maxima in both sweep directions

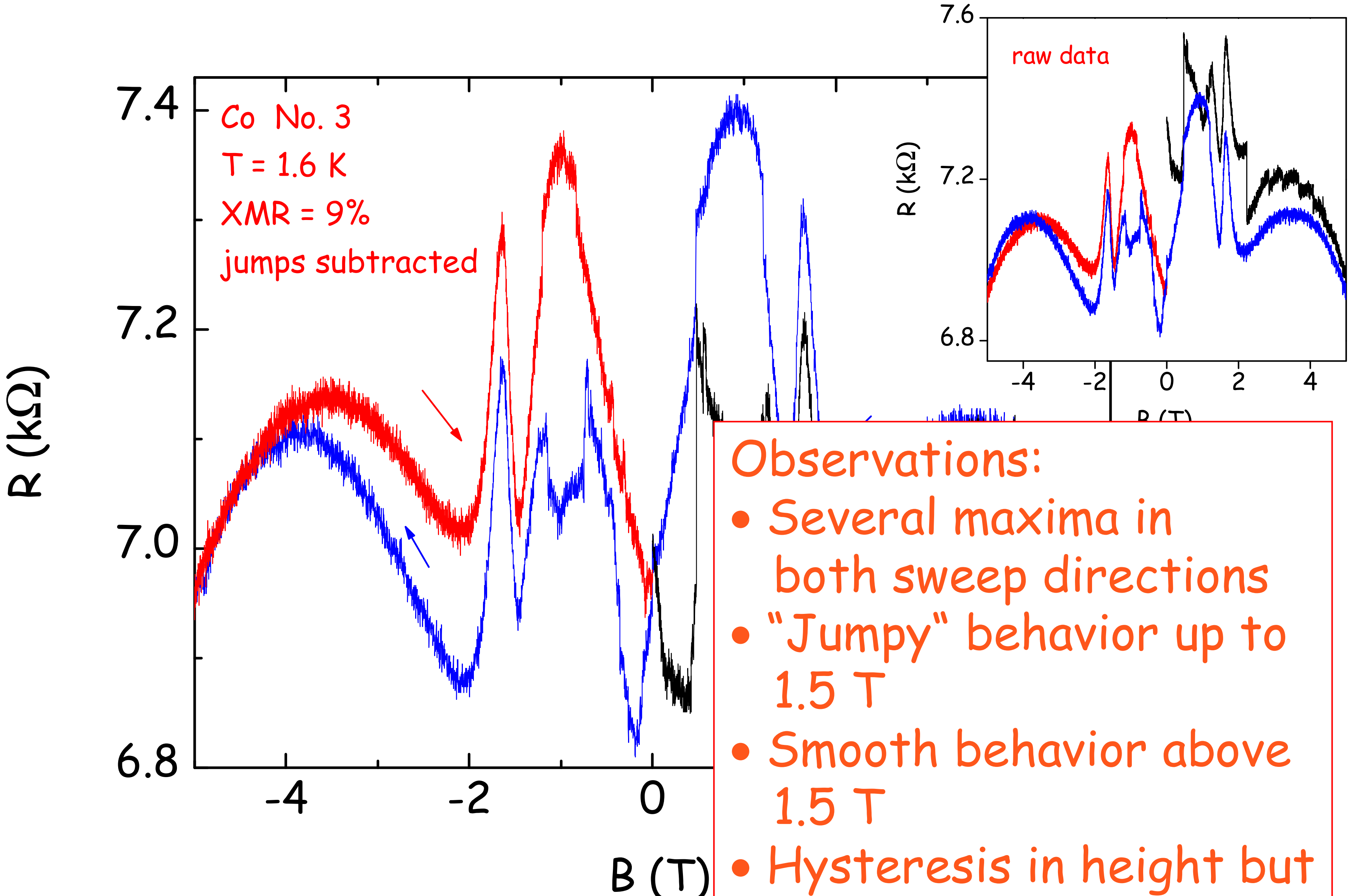
Magnetoresistance in perpendicular field



Observations:

- Several maxima in both sweep directions
- “Jumpy“ behavior up to 1.5 T
- Smooth behavior above 1.5 T

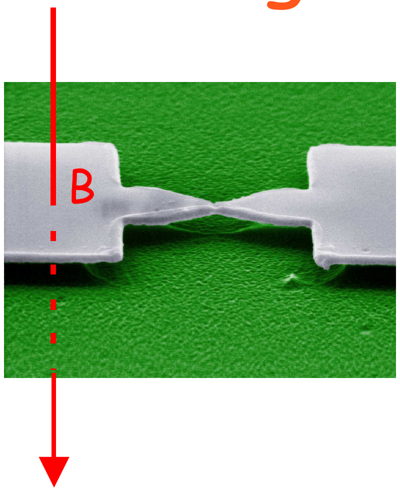
Magnetoresistance in perpendicular field

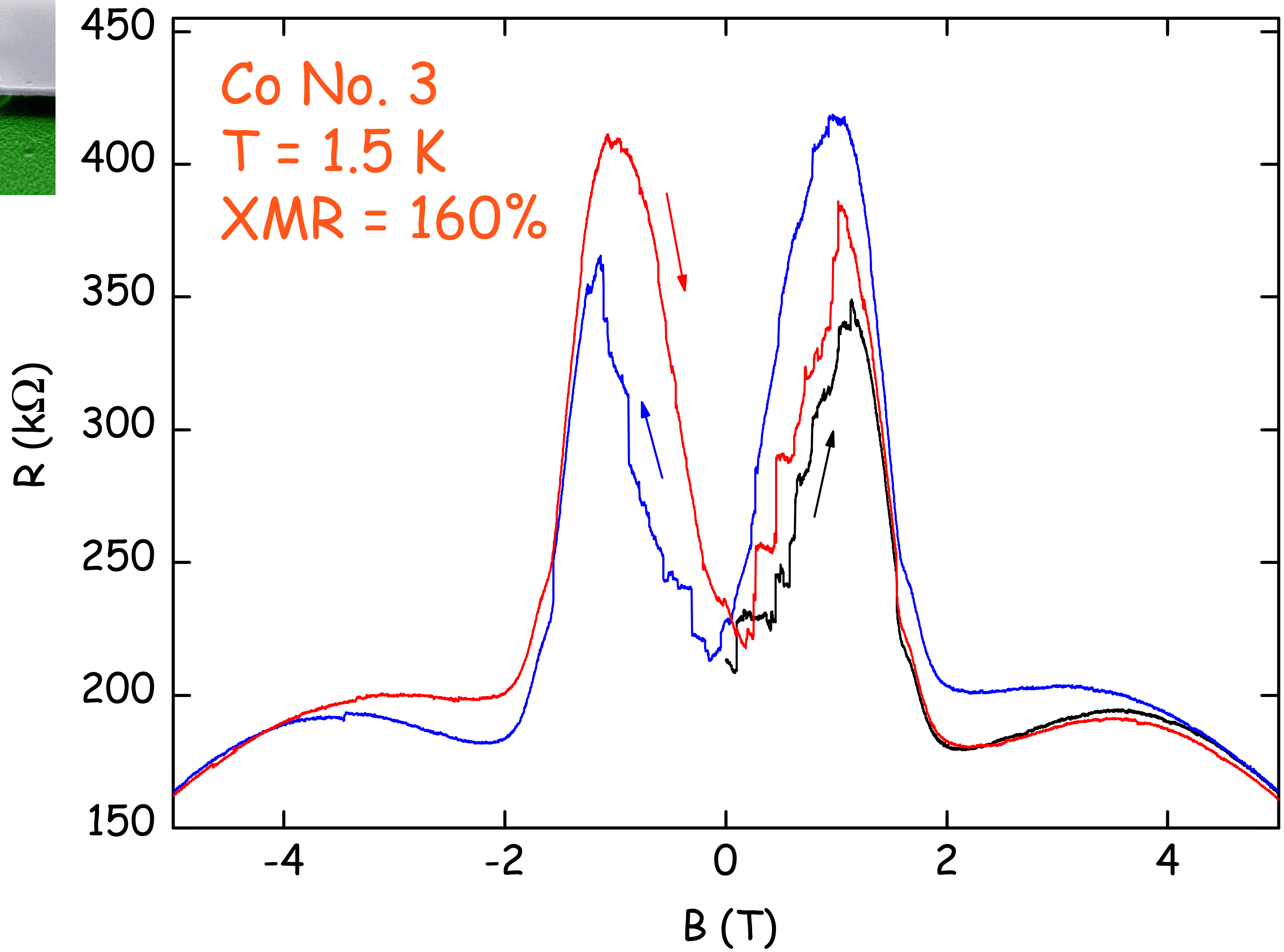


Observations:

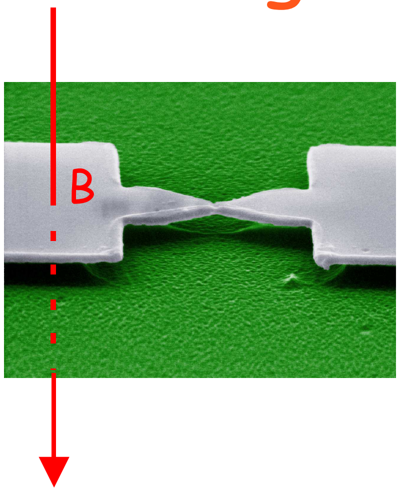
- Several maxima in both sweep directions
- "Jumpy" behavior up to 1.5 T
- Smooth behavior above 1.5 T
- Hysteresis in height but not in field position

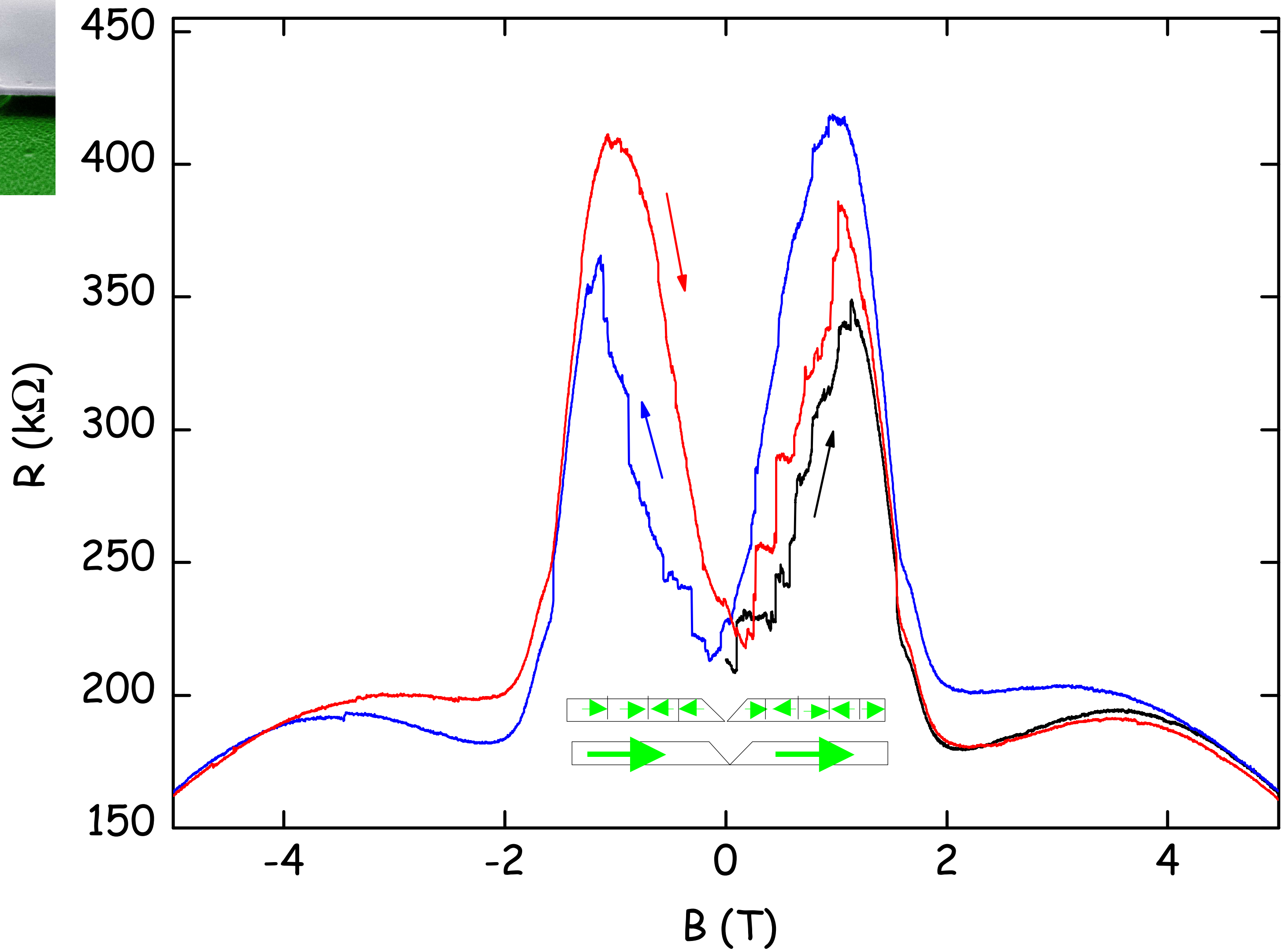
Magnetoresistance in tunneling regime



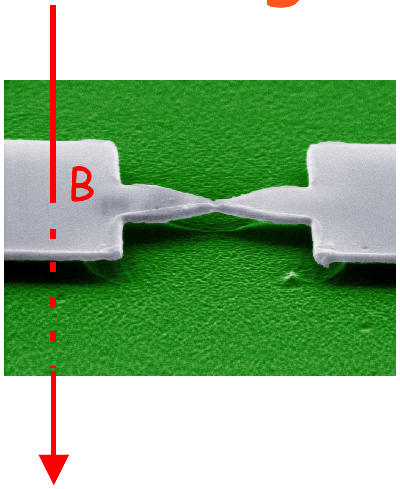


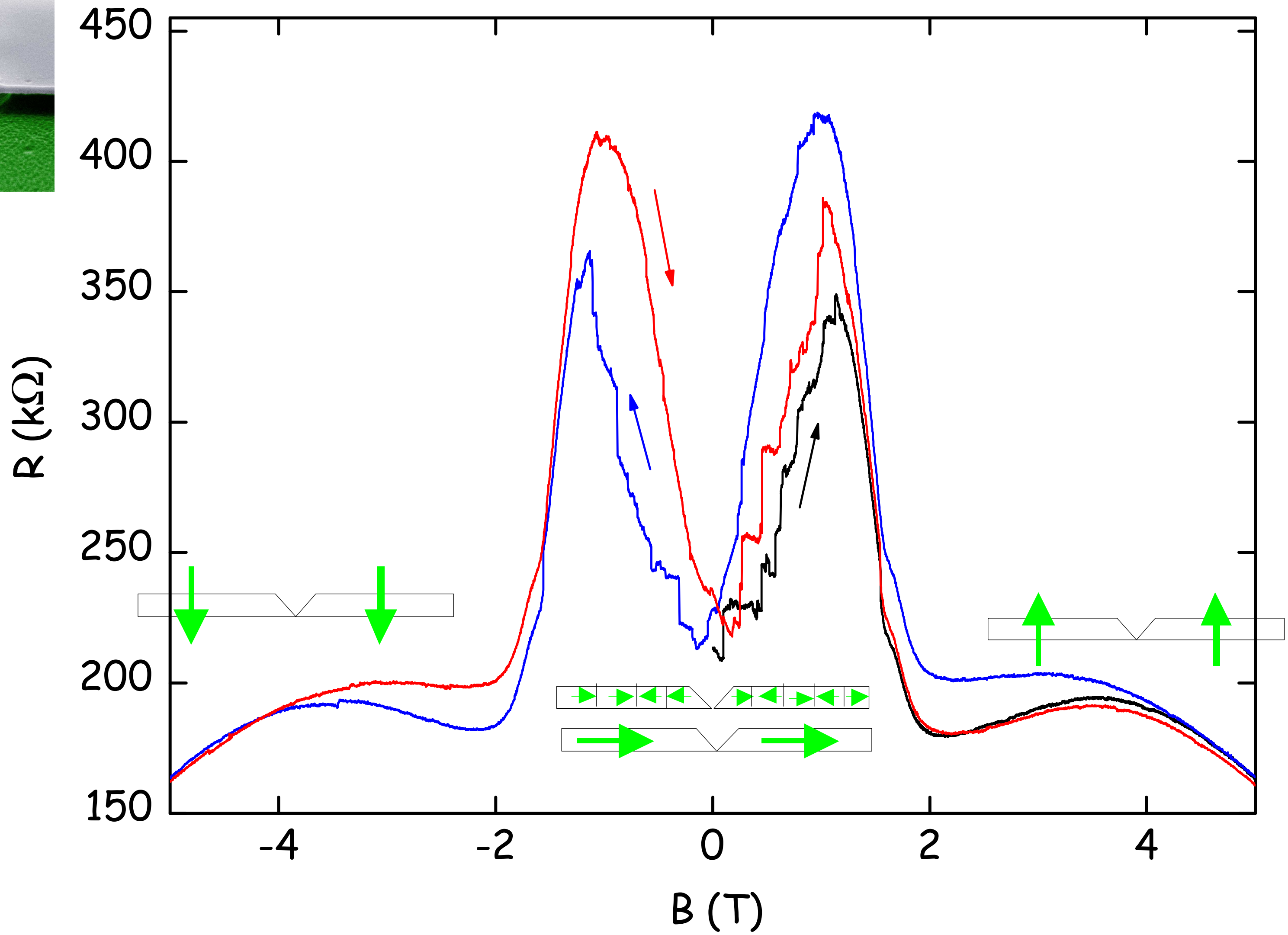
Magnetoresistance in tunneling regime



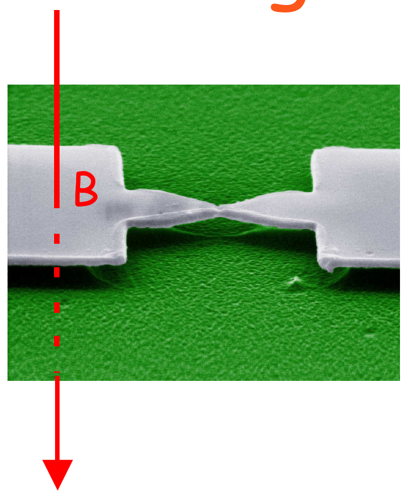


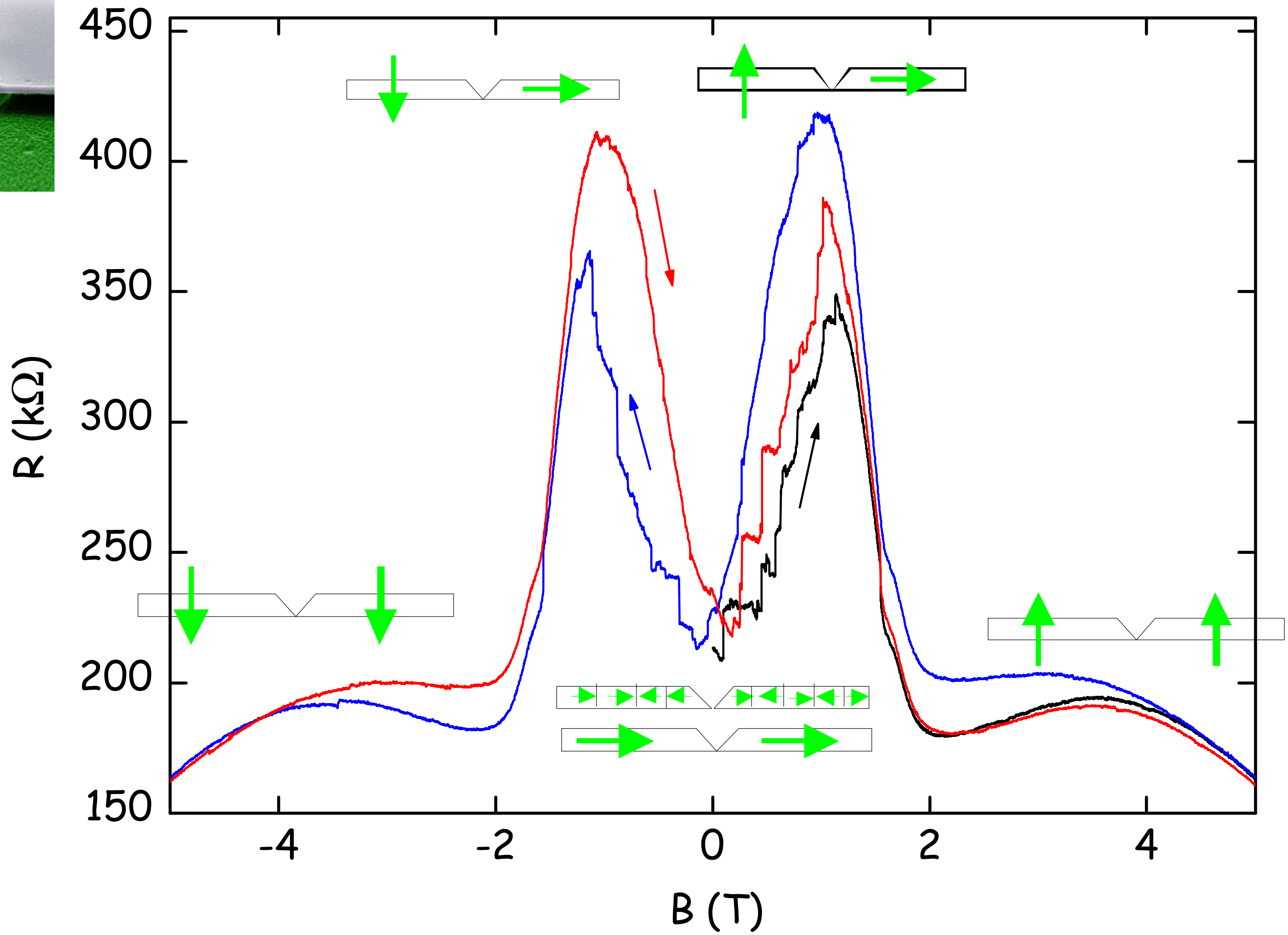
Magnetoresistance in tunneling regime



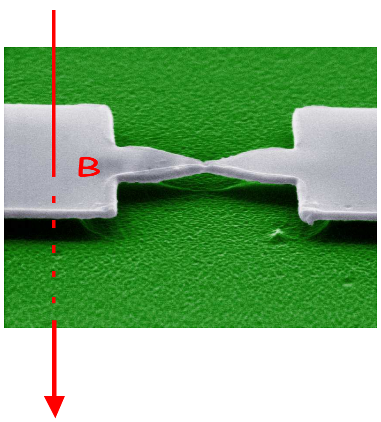


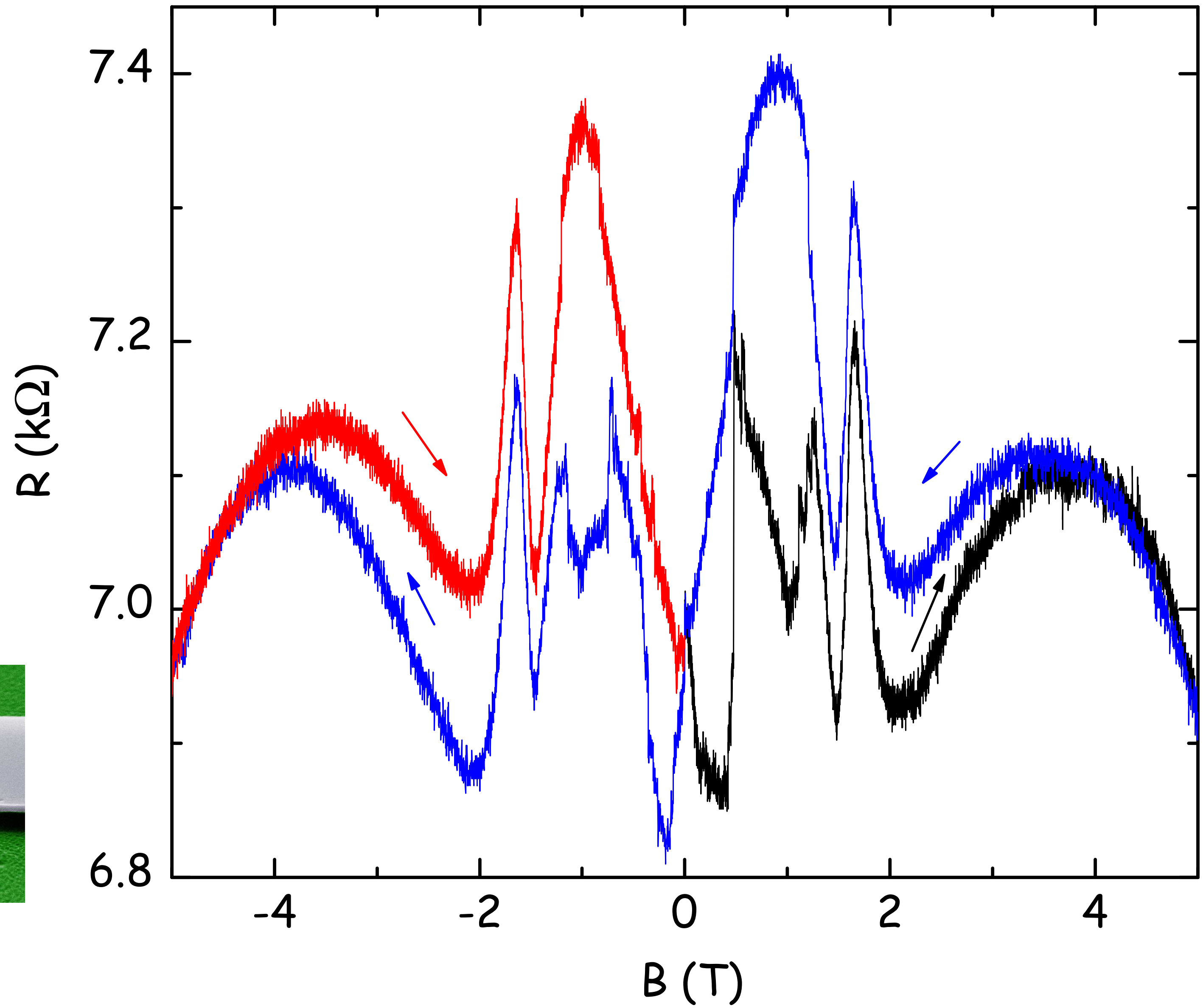
Magnetoresistance in tunneling regime



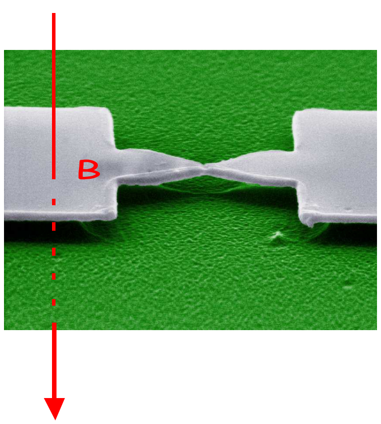


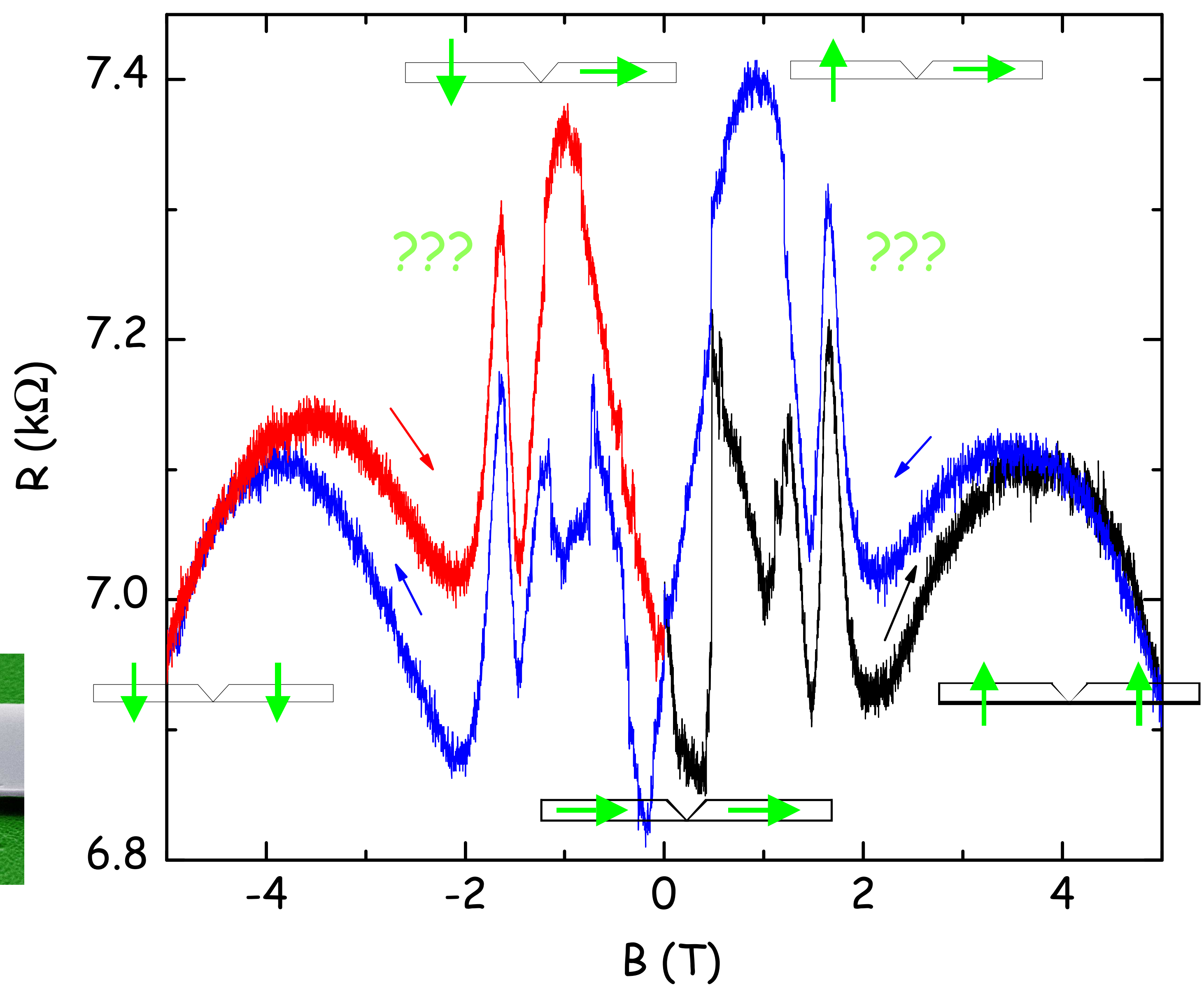
Magnetoresistance in perpendicular field





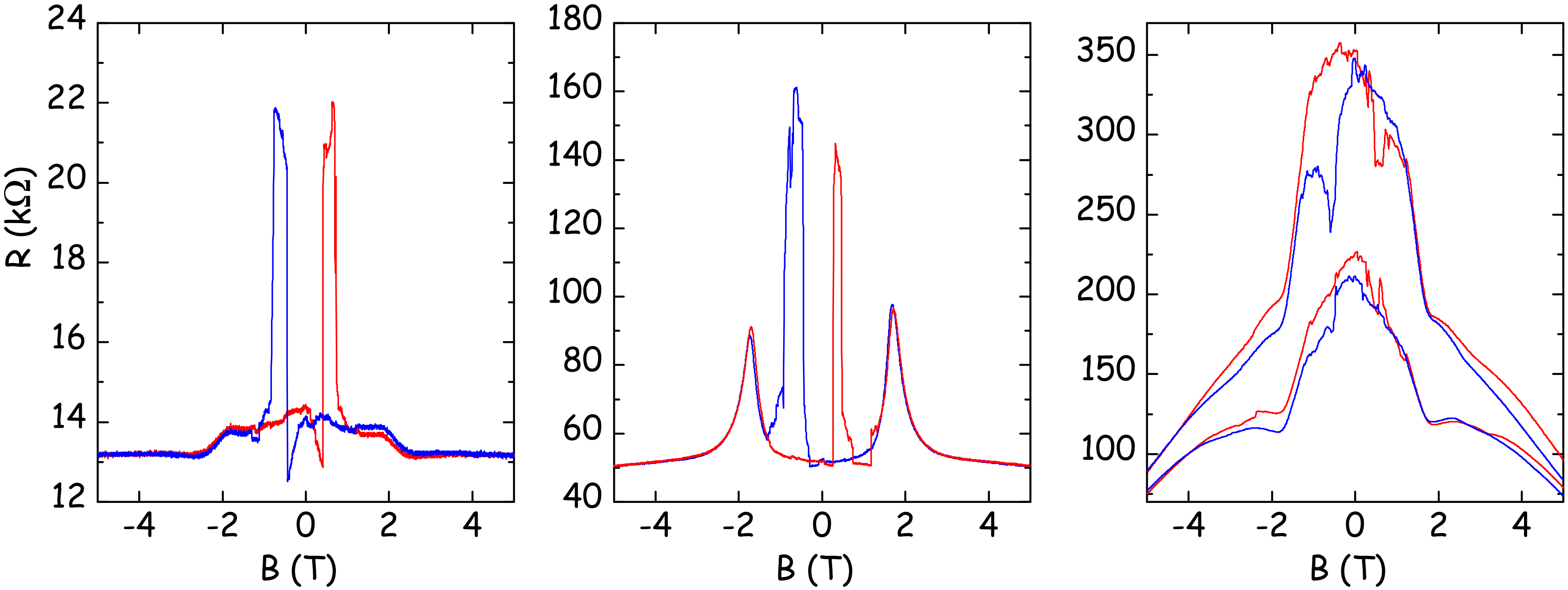
Magnetoresistance in perpendicular field





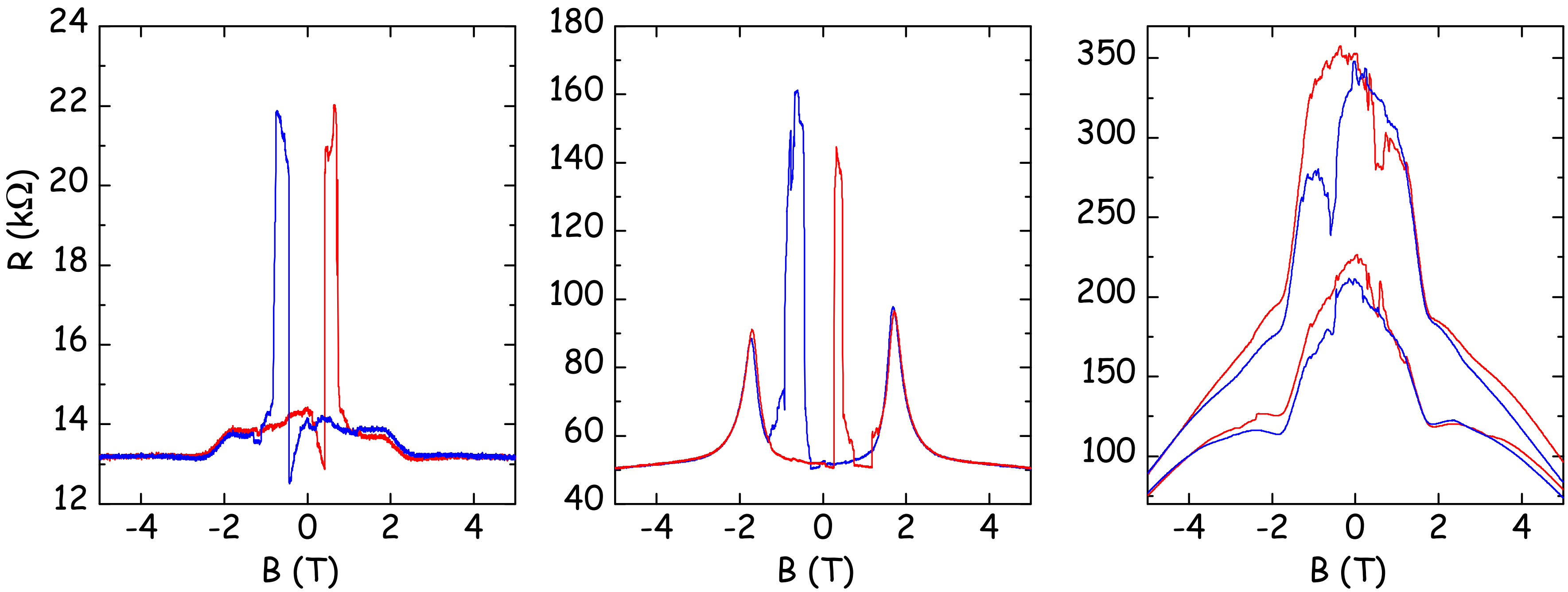
Magnetoresistance in perpendicular field

Co No. 2, T = 2 K



Magnetoresistance in perpendicular field

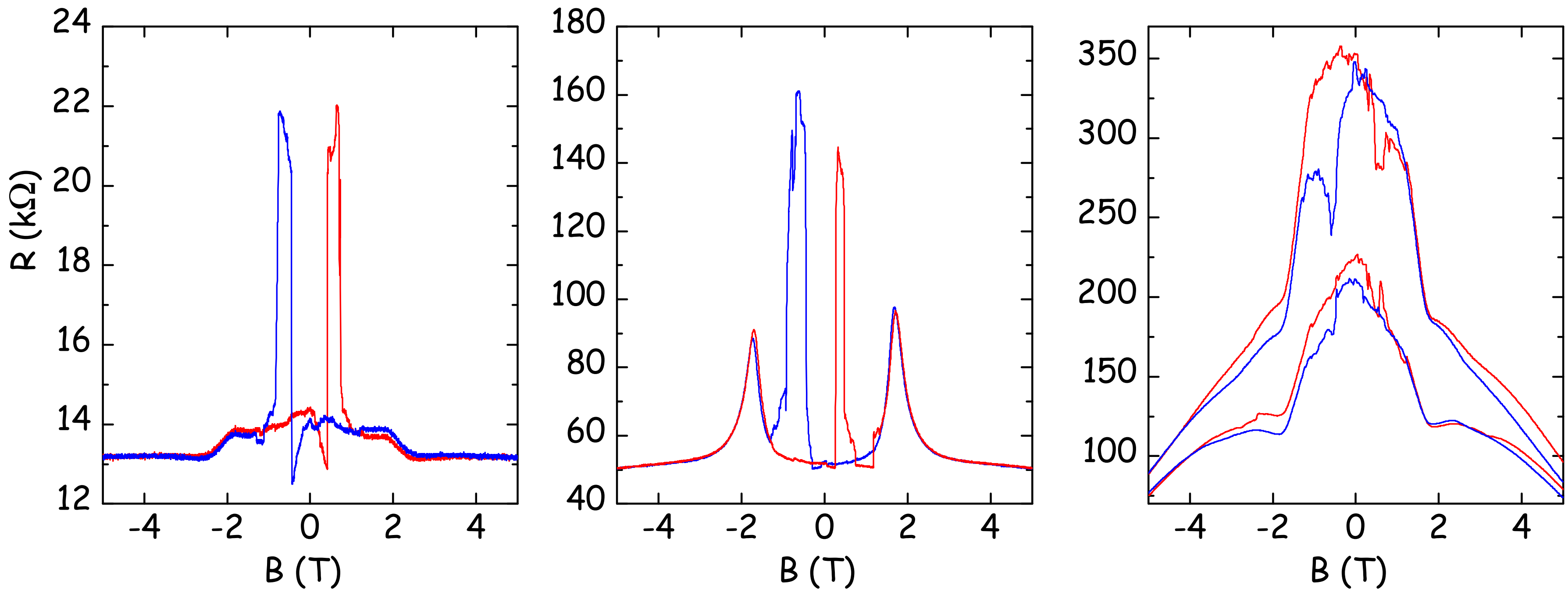
Co No. 2, T = 2 K



- low-field MR: maxima only when rising field size
- high-field MR: non-hysteretic, smooth maxima in both sweep directions at sample independent position

Magnetoresistance in perpendicular field

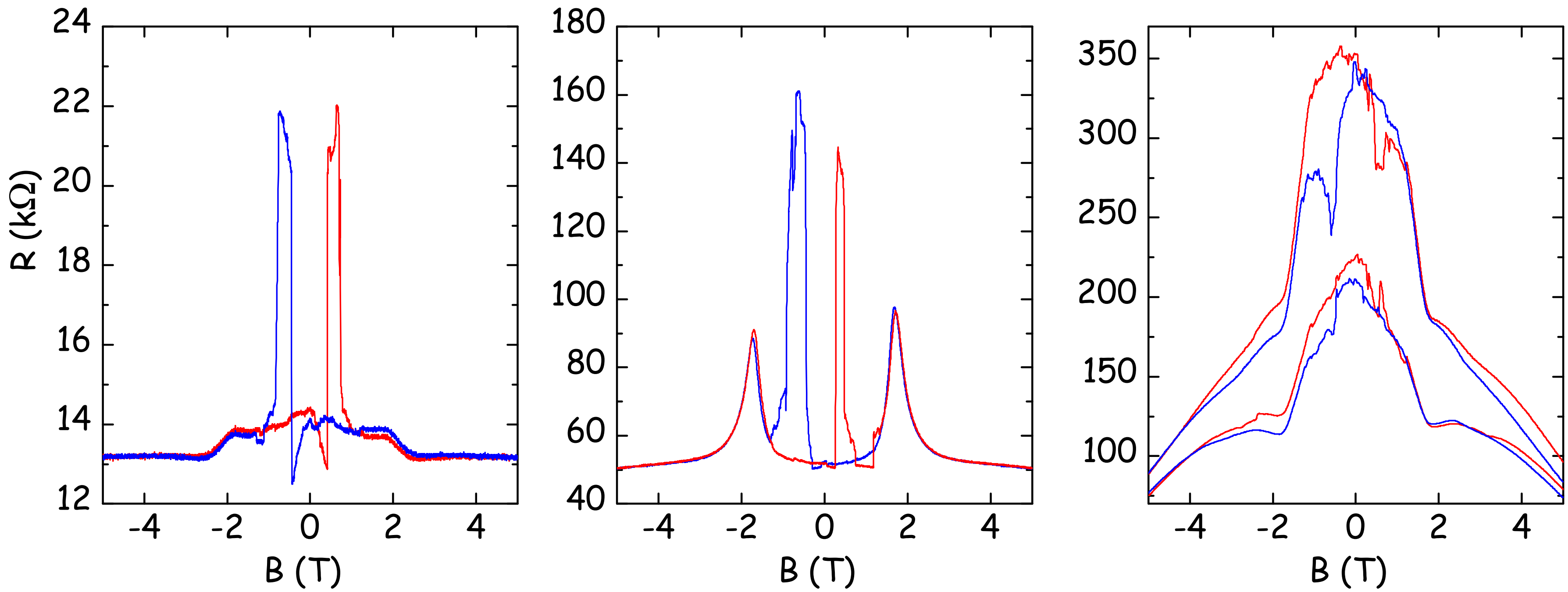
Co No. 2, T = 2 K



XMR = 69%

Magnetoresistance in perpendicular field

Co No. 2, T = 2 K

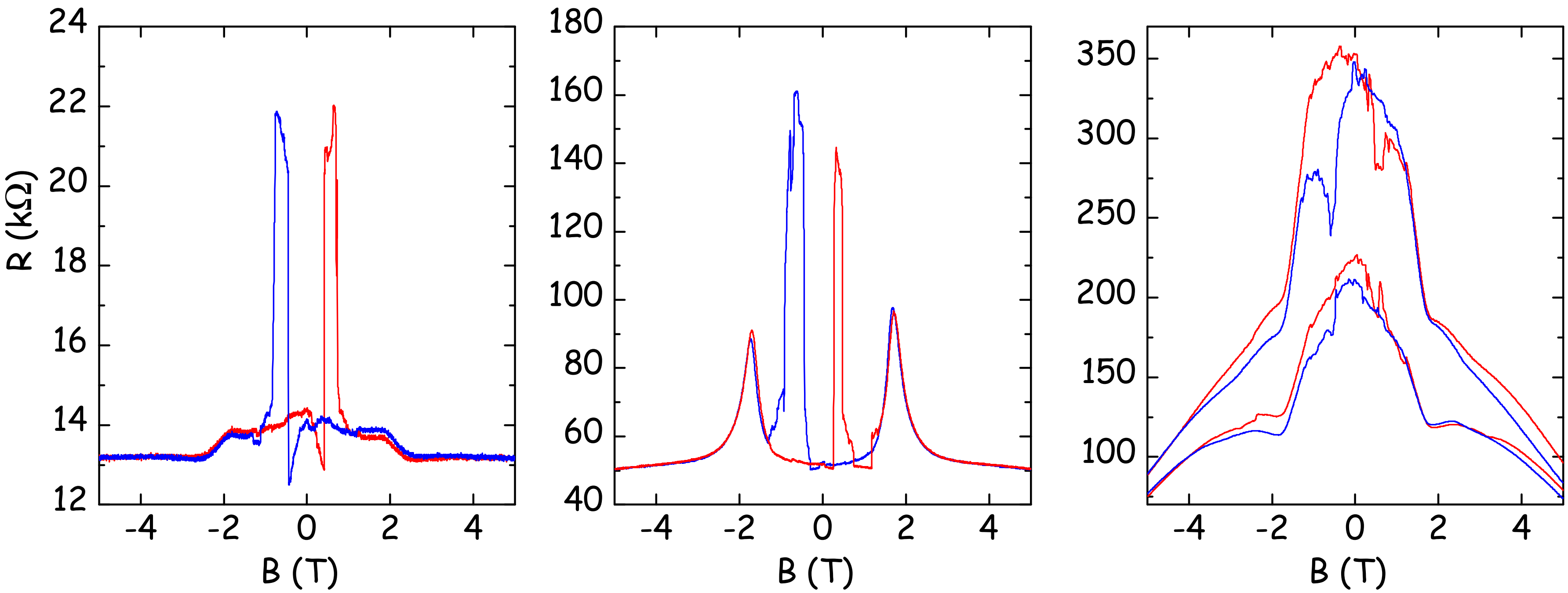


XMR = 69%

XMR = 220%

Magnetoresistance in perpendicular field

Co No. 2, T = 2 K



XMR = 69%

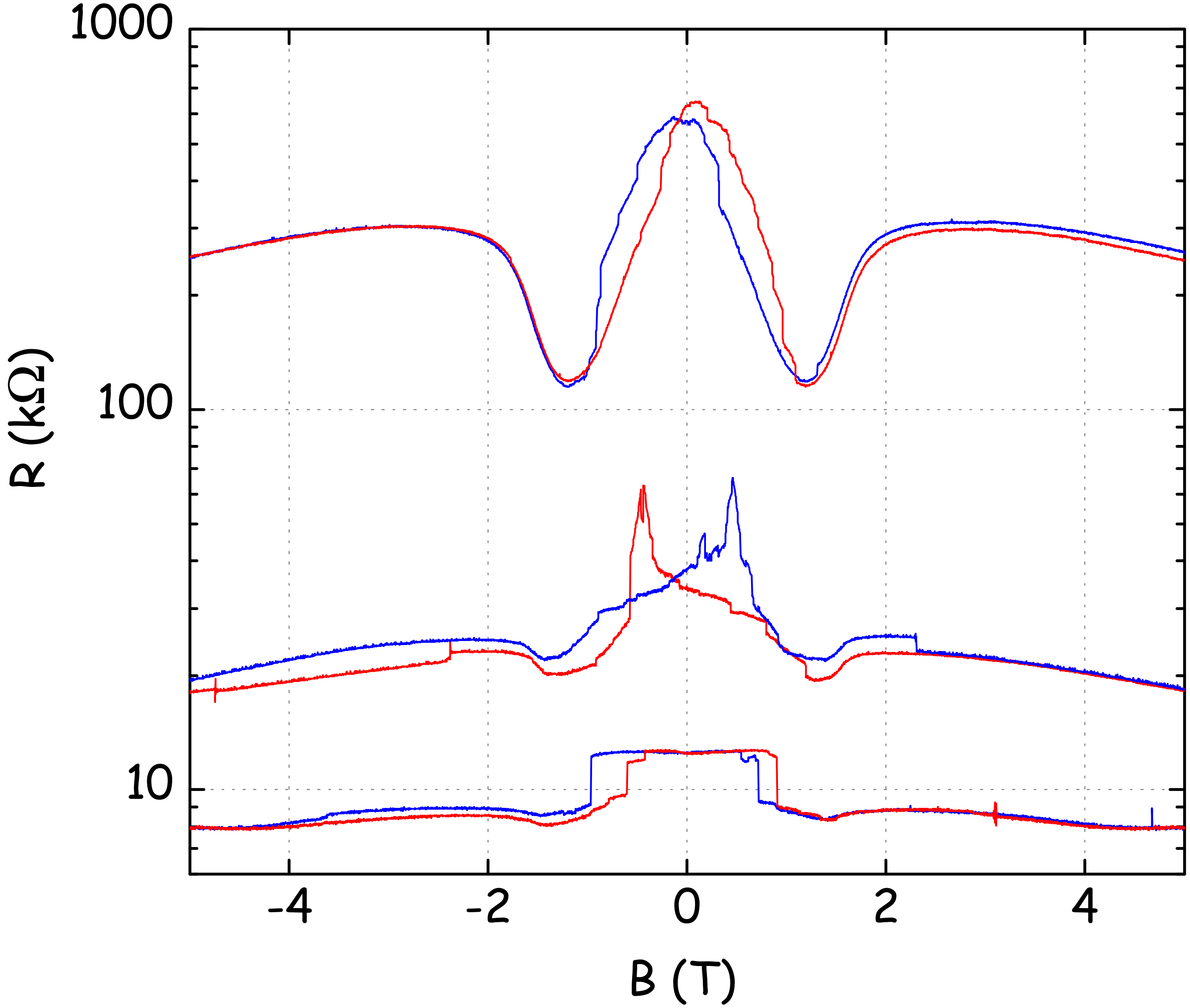
XMR = 220%

XMR = 370%

XMR = 270%

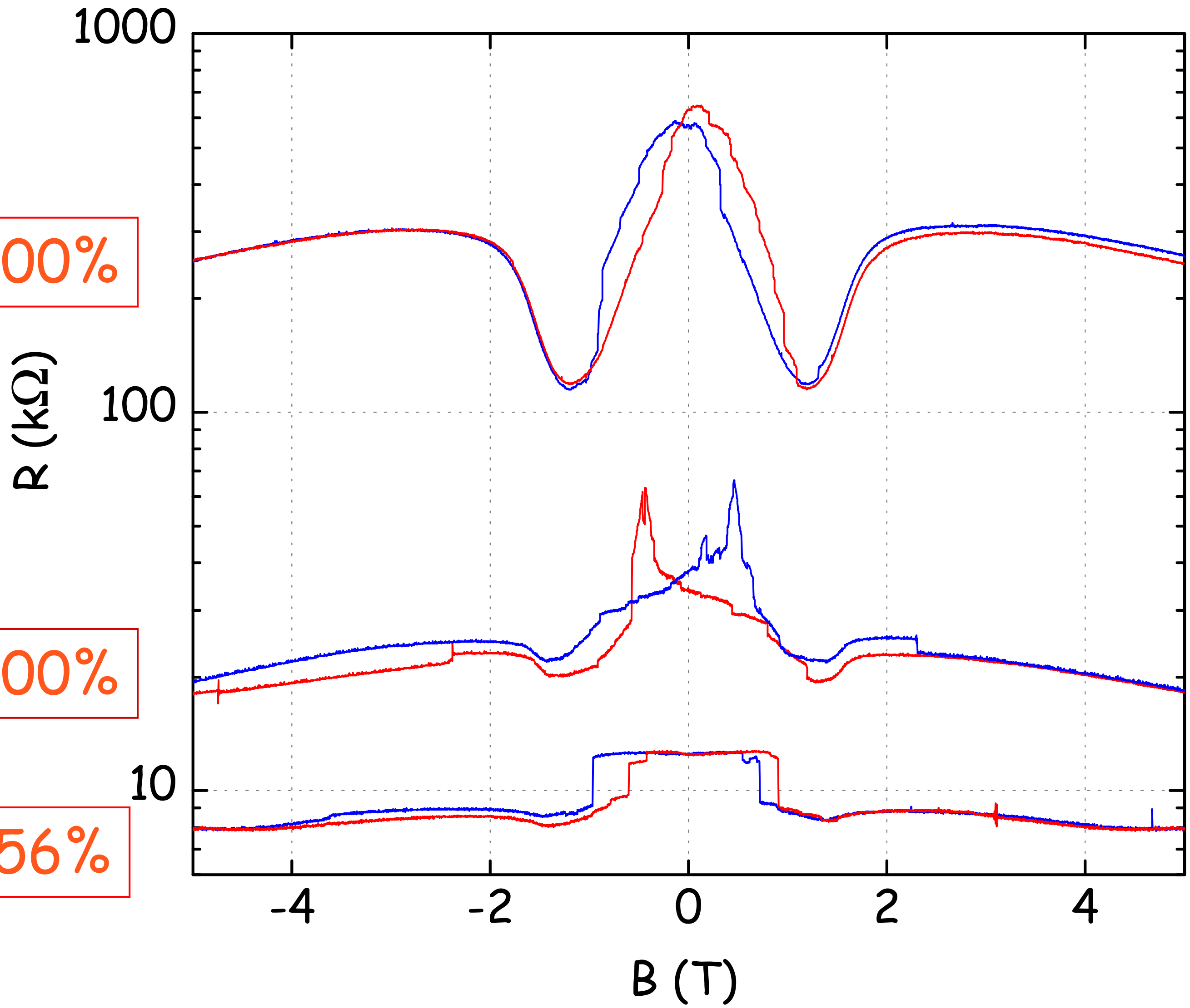
Magnetoresistance in perpendicular field

Co. 1, T = 1.5 K



Magnetoresistance in perpendicular field

Co No. 1, T = 1.5 K

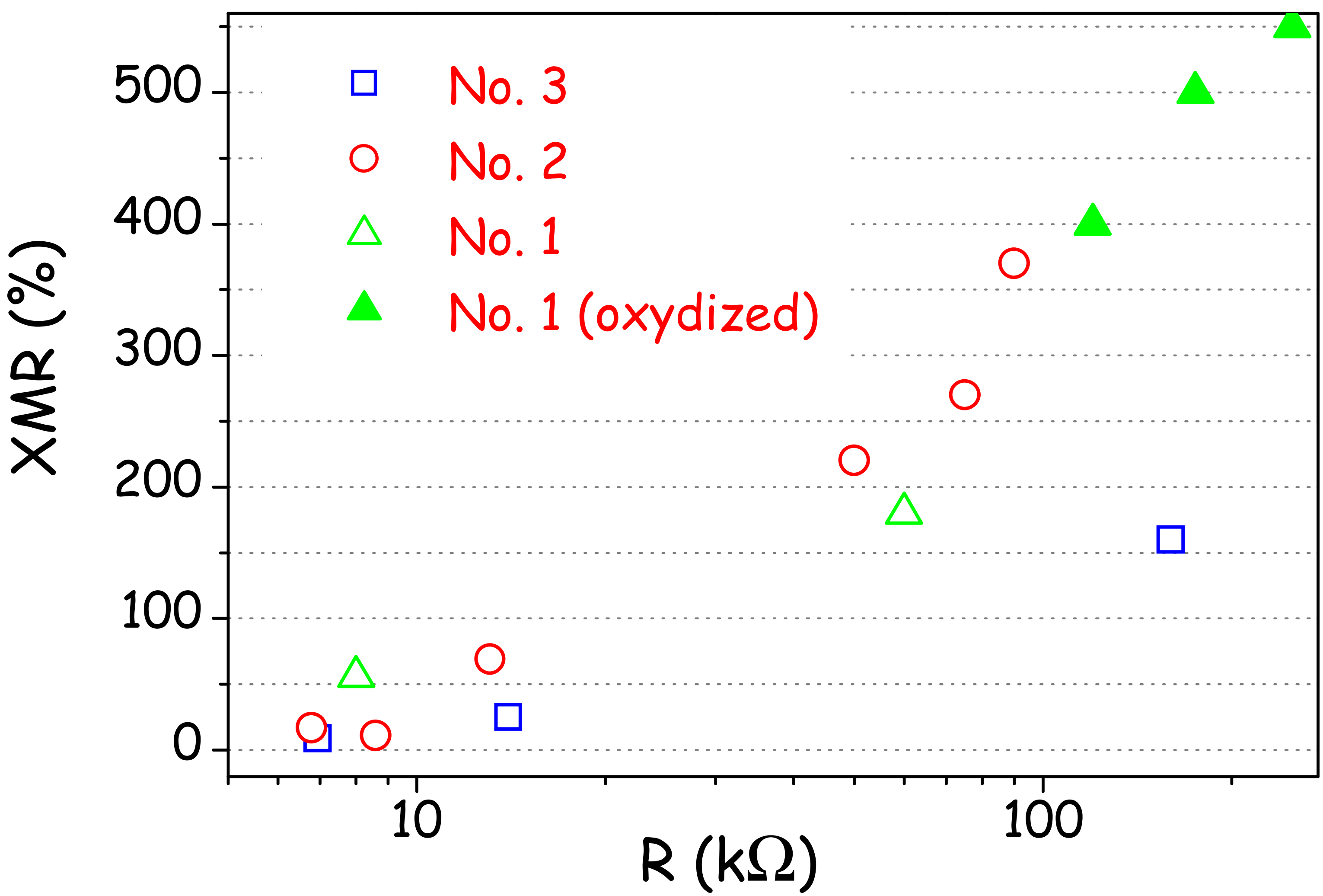


XMR = 400%

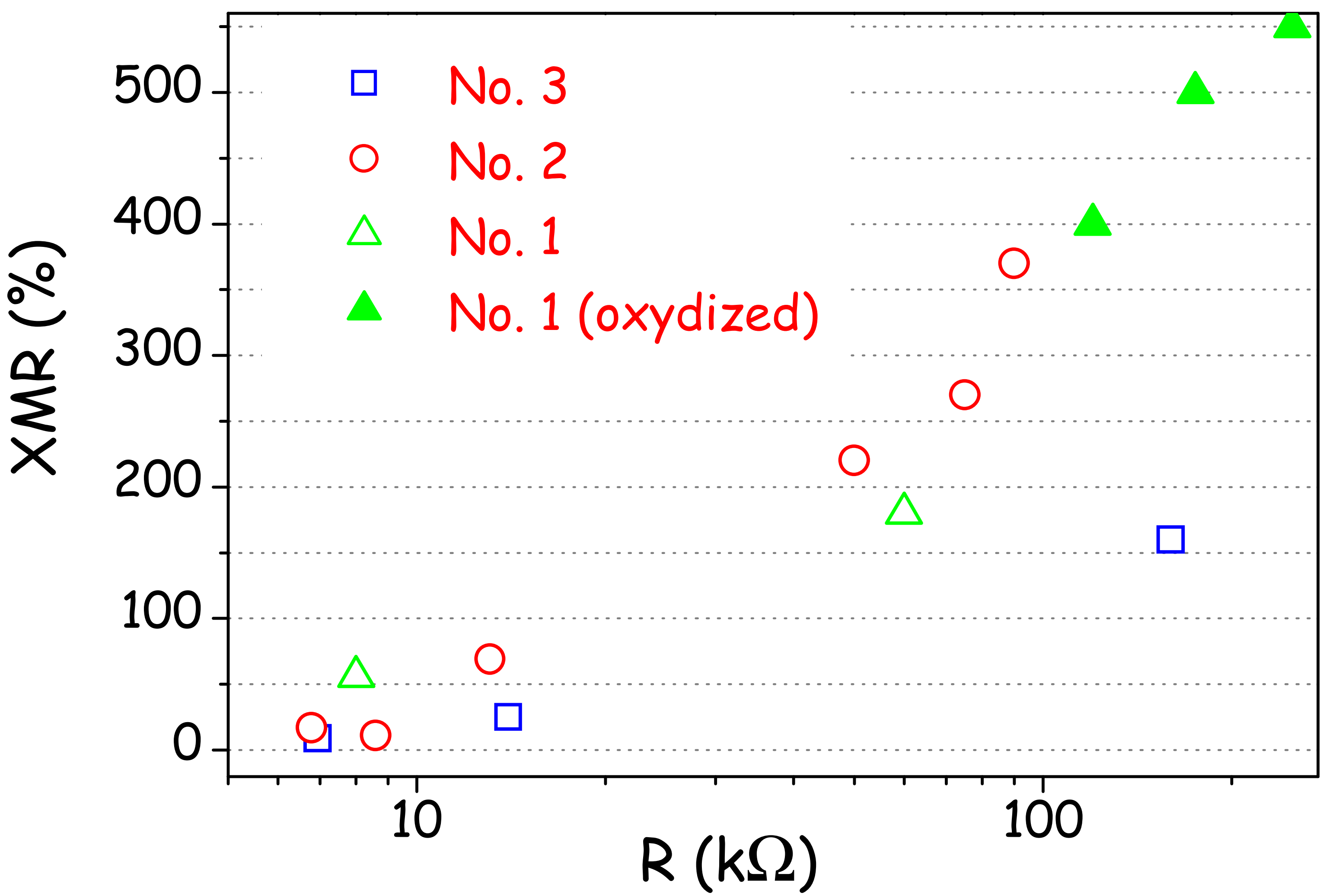
XMR = 200%

XMR = 56%

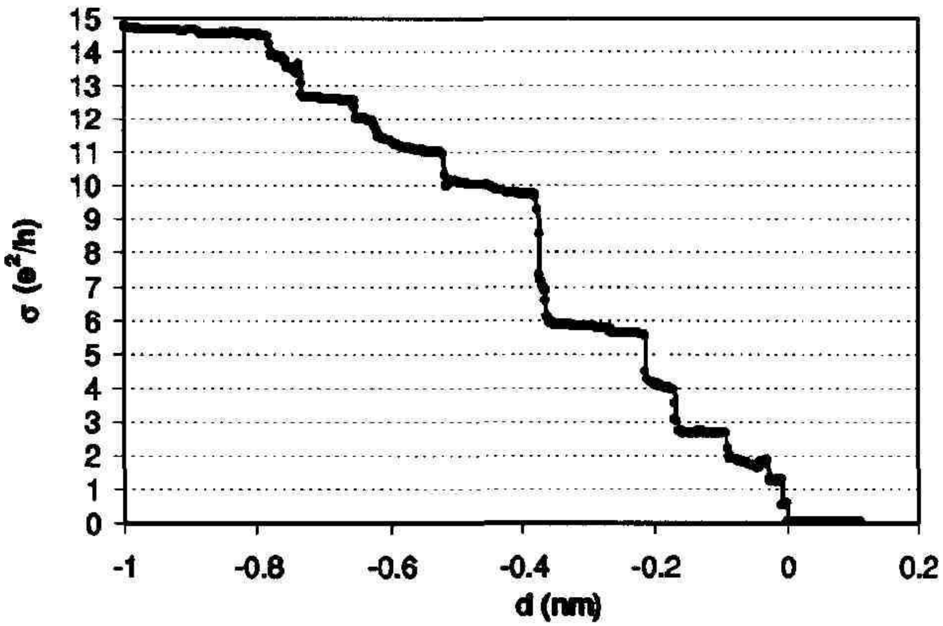
Resistance changes of Co contacts



Resistance changes of Co contacts



Magnetoresistance of Ni lithographic breakjunctions



Viret et al. PRB 2001

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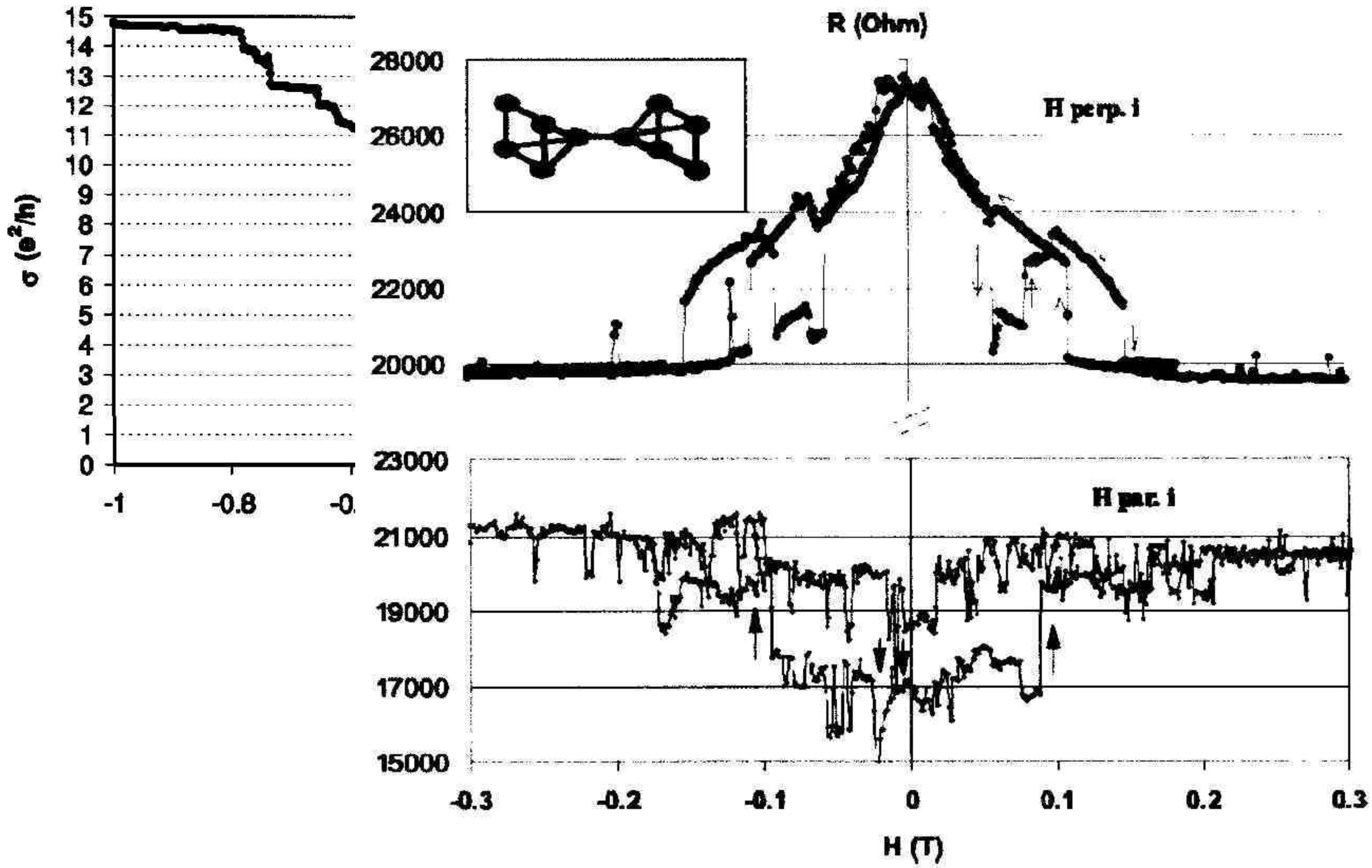

Viret et al. PRB 2001

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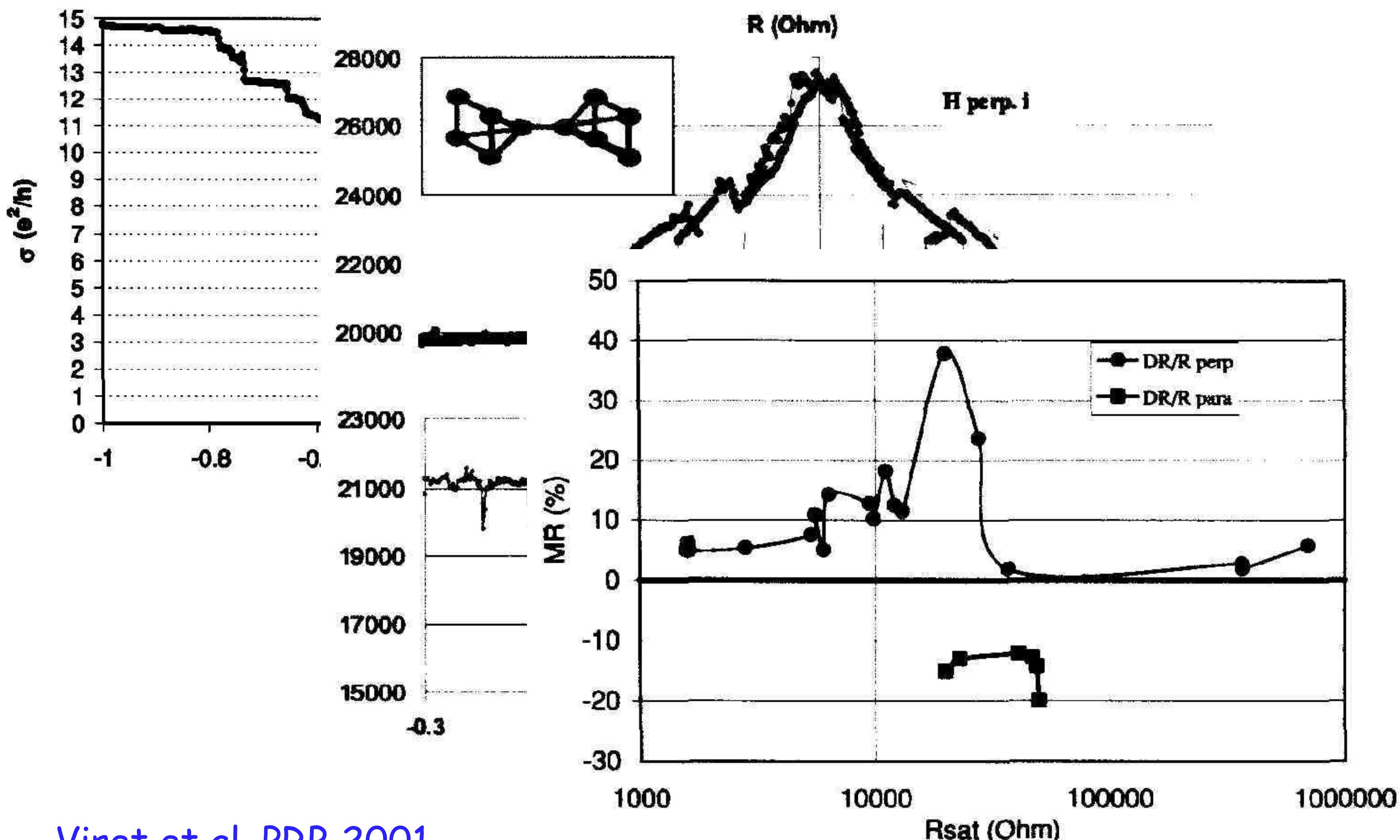
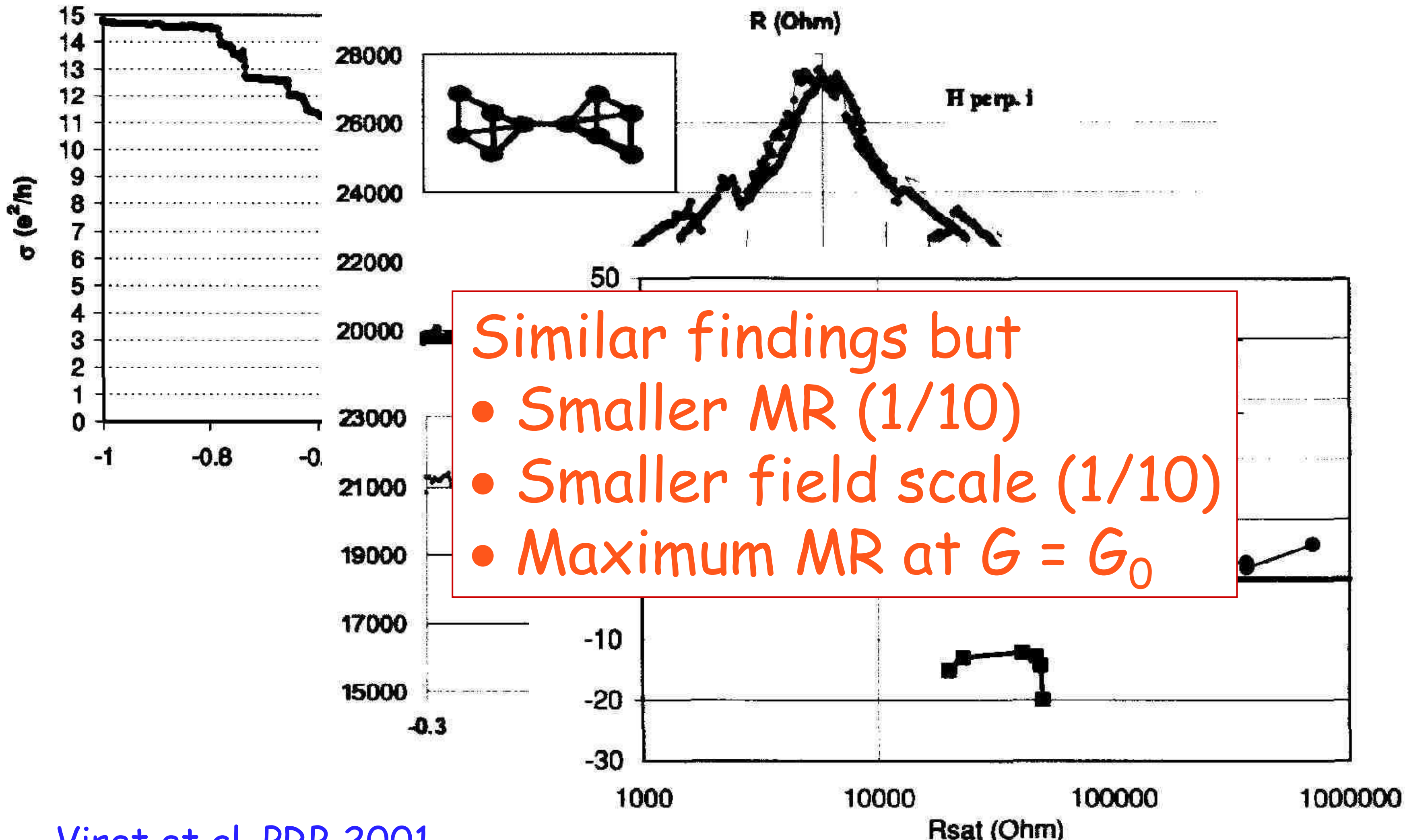


Viret et al. PRB 2001

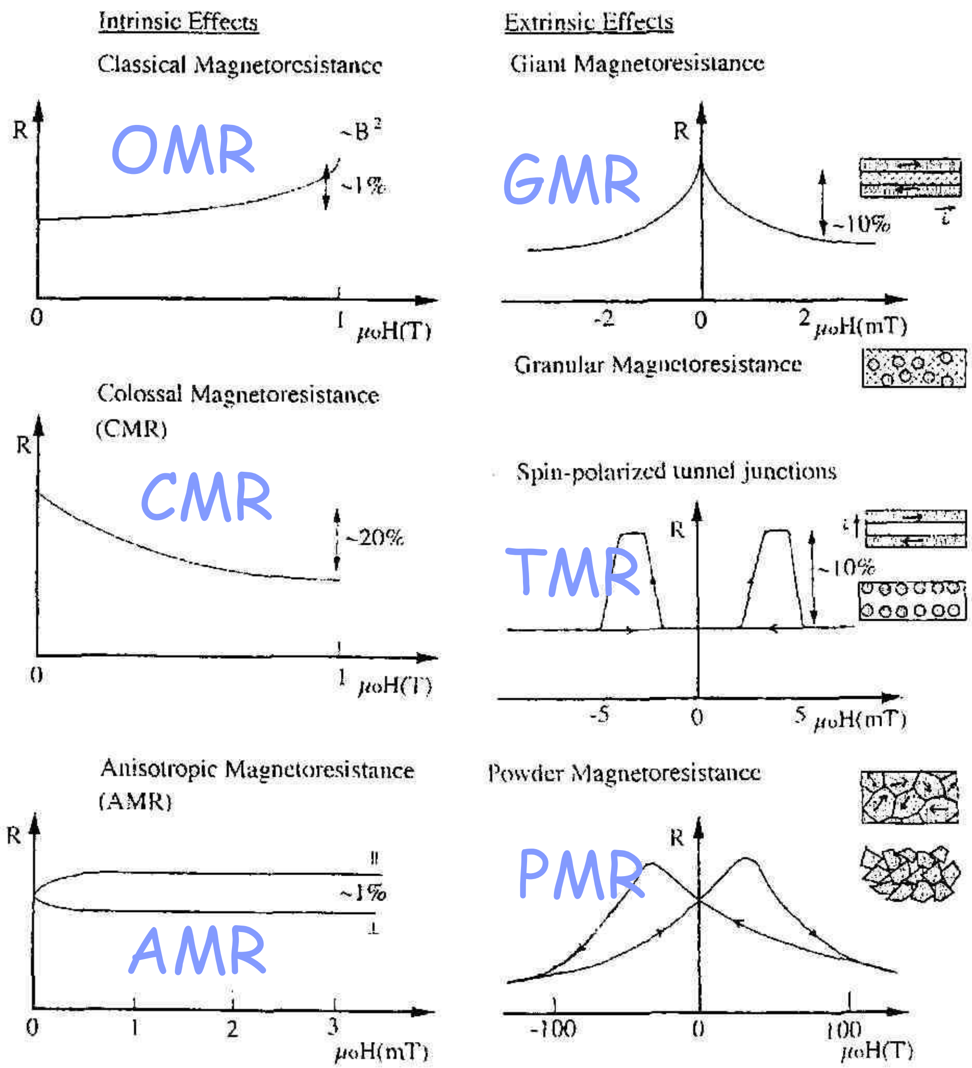
Magnetoresistance of Ni lithographic breakjunctions



Similar findings but
- Smaller MR (1/10)
- Smaller field scale (1/10)
- Maximum MR at $G = G_0$

Viret et al. PRB 2001

Origin of strong MR?



Coey et al., APL 99

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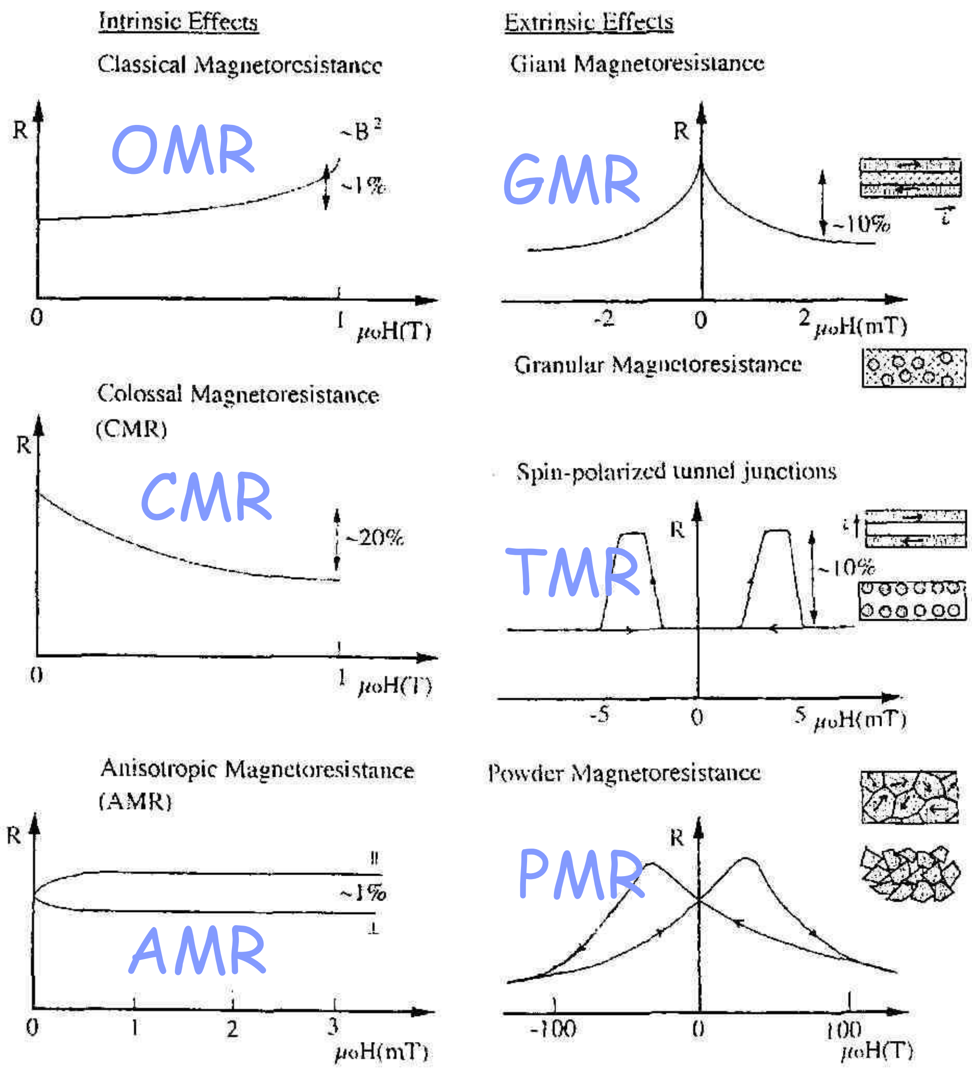

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Other possibilites:

BMR: Ballistic Magnetoresistance

Assumption: quantized channel transmissions

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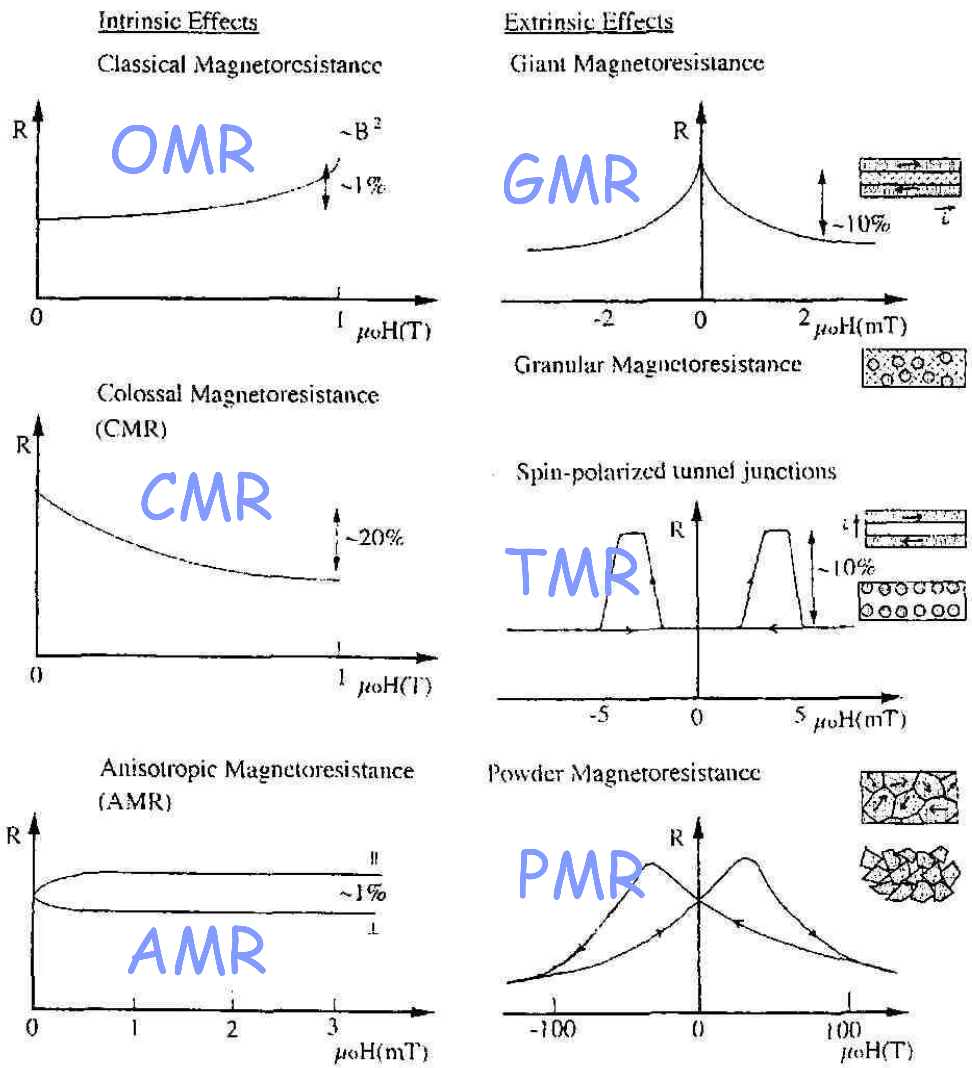

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Magnetostriction

Should be small in perp. field, monotonic

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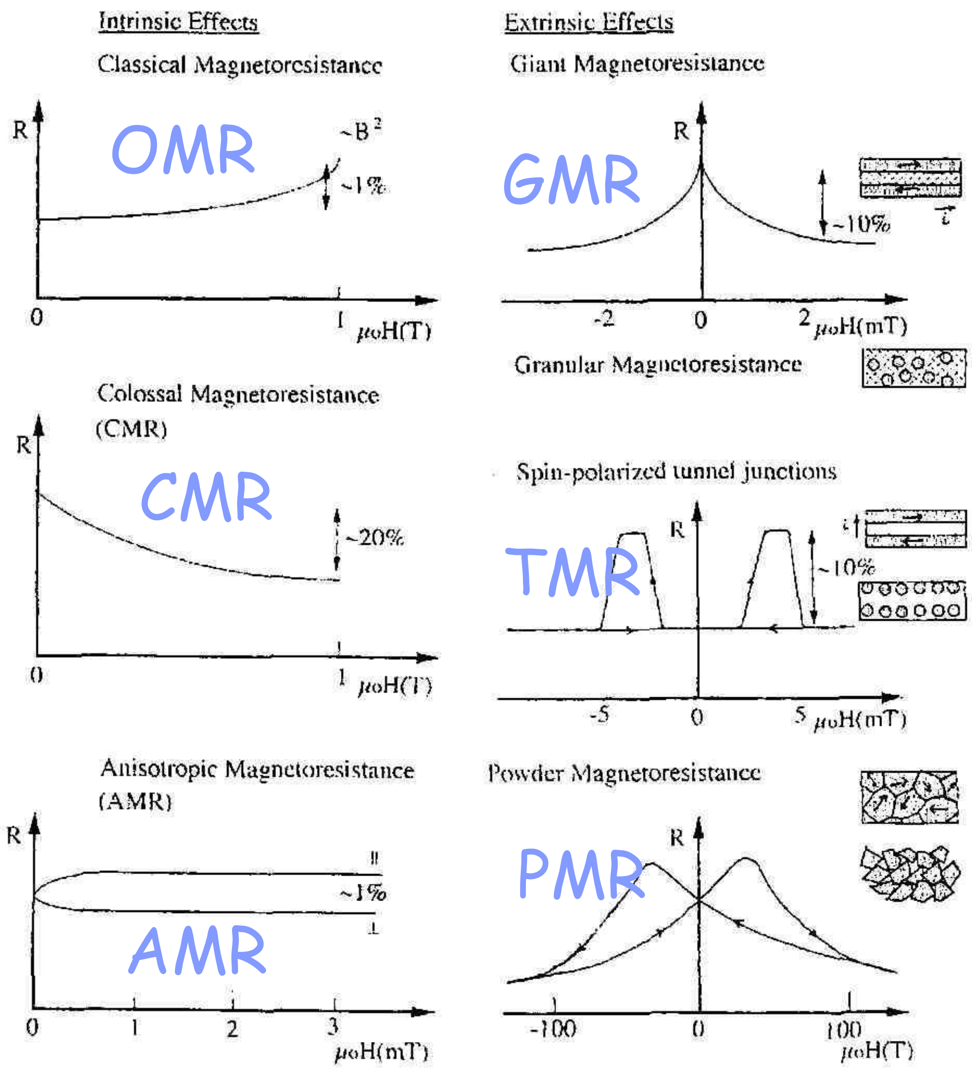

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Channels determined by LCAO

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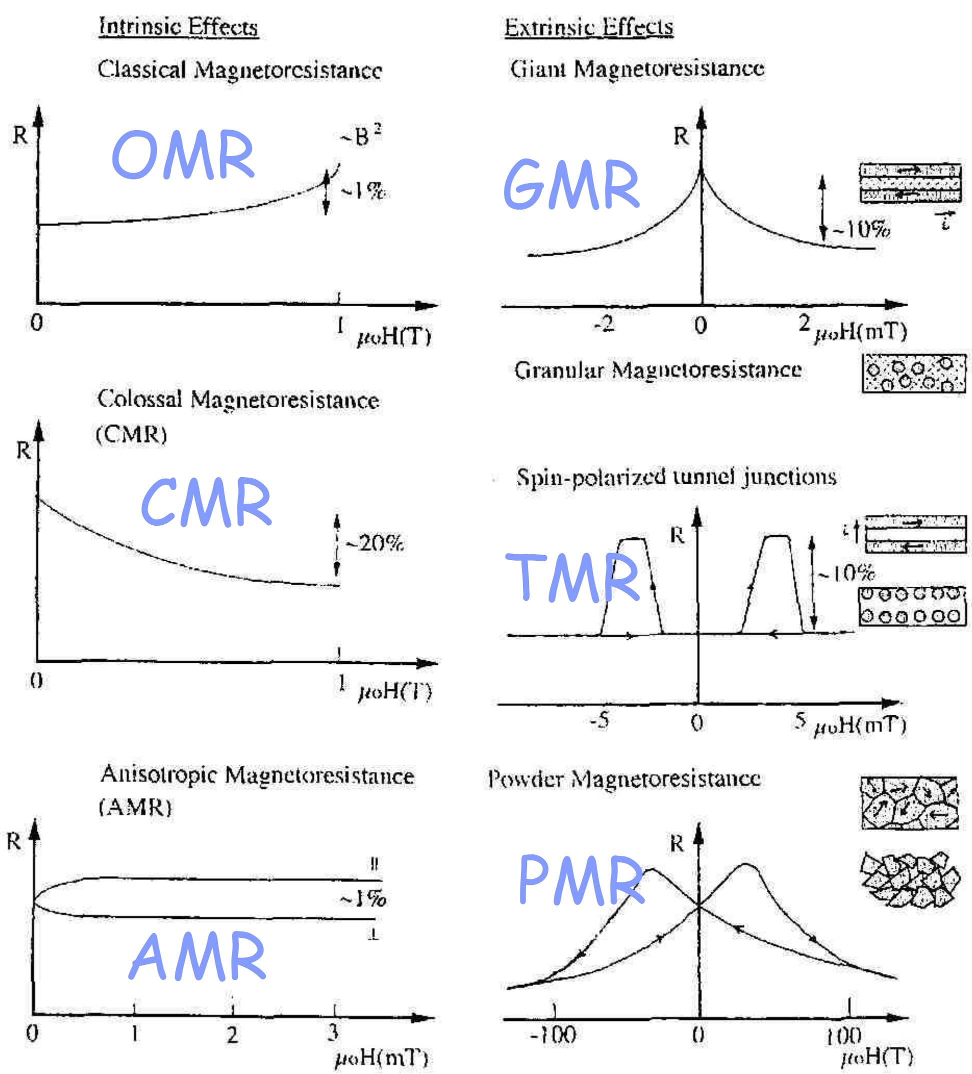

Coey et al., APL 99

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Assumption: quantized channel transmissions

Magnetostriction

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Field dependence of channels

Channels determined by LCAO

What else?

Measurement of transport channels

Shot noise: v. d. Brom & v. Ruitenbeek, PRL 82 (1999) 1526, R. Cron et al., PRL 86 (2001) 4104

$$S \propto \sum_i \tau_i (1-\tau_i)$$

Conductance fluctuations: Ludoph et al., PRL 82 (1999) 1530

$$\Delta G \propto \sum_i \tau_i^2 (1-\tau_i)$$

Thermopower: Ludoph et al., PRB 59 (1999) 12290

$$U \propto \sum_i \tau_i^2 (1-\tau_i)$$

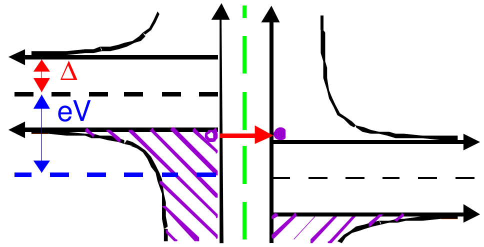
Supercurrent: Goffman et al., PRL 85 (2000) 170

$$I_J \propto \sum_i \tau_i (1-\tau_i \sin^2(\delta/2))^{-1/2} \cos(\delta/2)$$

Superconducting IVs: Scheer et al., PRL 78 (1997) 3535

Superconductivity: Nonlinear IV characteristics by MAR

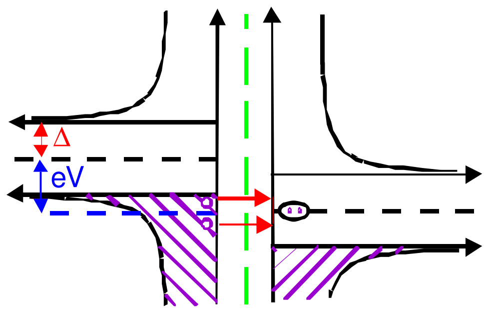
single-electron transport



$eV \geq 2\Delta/1$

$P \propto \tau^{1}$

2 electrons:

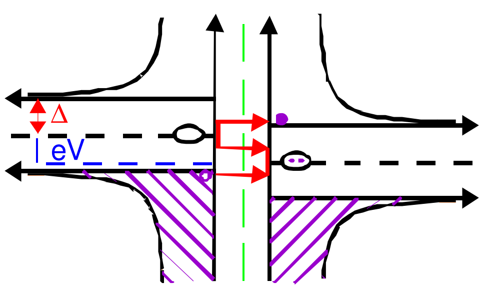


$eV \geq 2\Delta/2$

$P \propto \tau^{2}$

Andreev reflection

3 electrons:



$eV \geq 2\Delta/3$

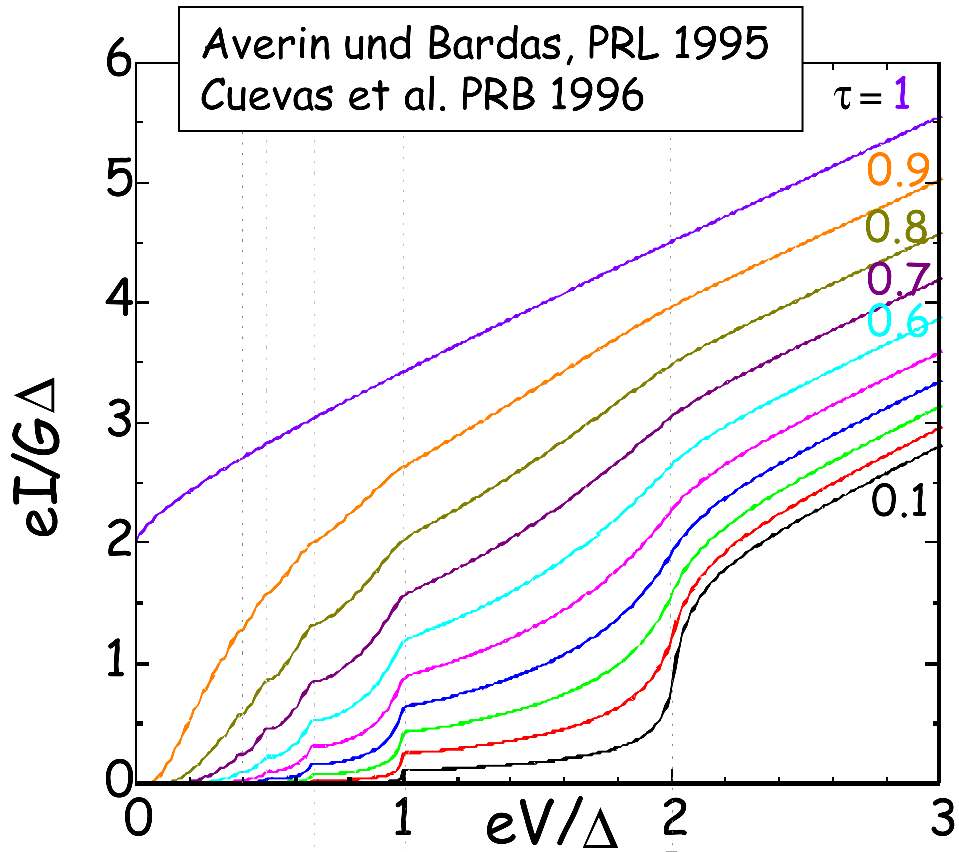
$P \propto \tau^{3}$

multiple Andreev reflection (MAR)

m electrons:

$eV \geq 2\Delta/m$

$P \propto \tau^{m}$



3 e⁻ transfered
2 qp created
$eV > 2\Delta/3$
$P \propto \tau^{3}$

2 e⁻ transfered
2 qp created
$eV > 2\Delta/2$
$P \propto \tau^{2}$

1 e⁻ transfered
2 qp created
$eV > 2\Delta/1$
$P \propto \tau$

SPECTROSCOPY OF THE CHANNEL ENSEMBLE

- Decomposition of exp. IVs into contributions of N channels with transmission coefficients $\{\tau_1, \tau_2, \tau_3, \ldots\ldots, \tau_N\}$

$$I_{\exp} = \sum_{i=1}^{N} i(V, \tau_i)$$

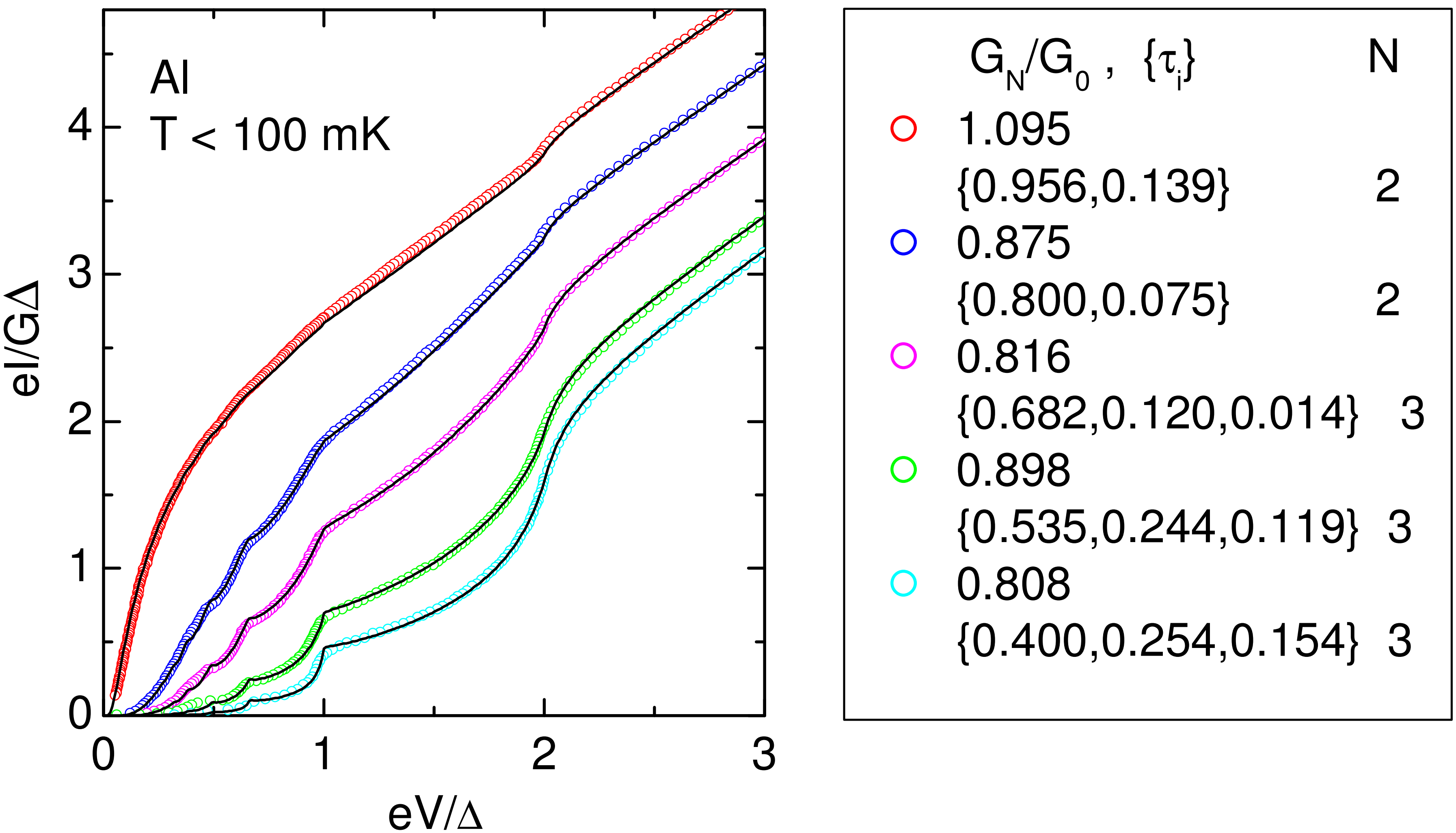
$i(V, \tau_i)$: current contribution of channel with τ_i

- (total) conductance G: $$G = G_0 \sum_{i=1}^{N} \tau_i = G_0 D$$

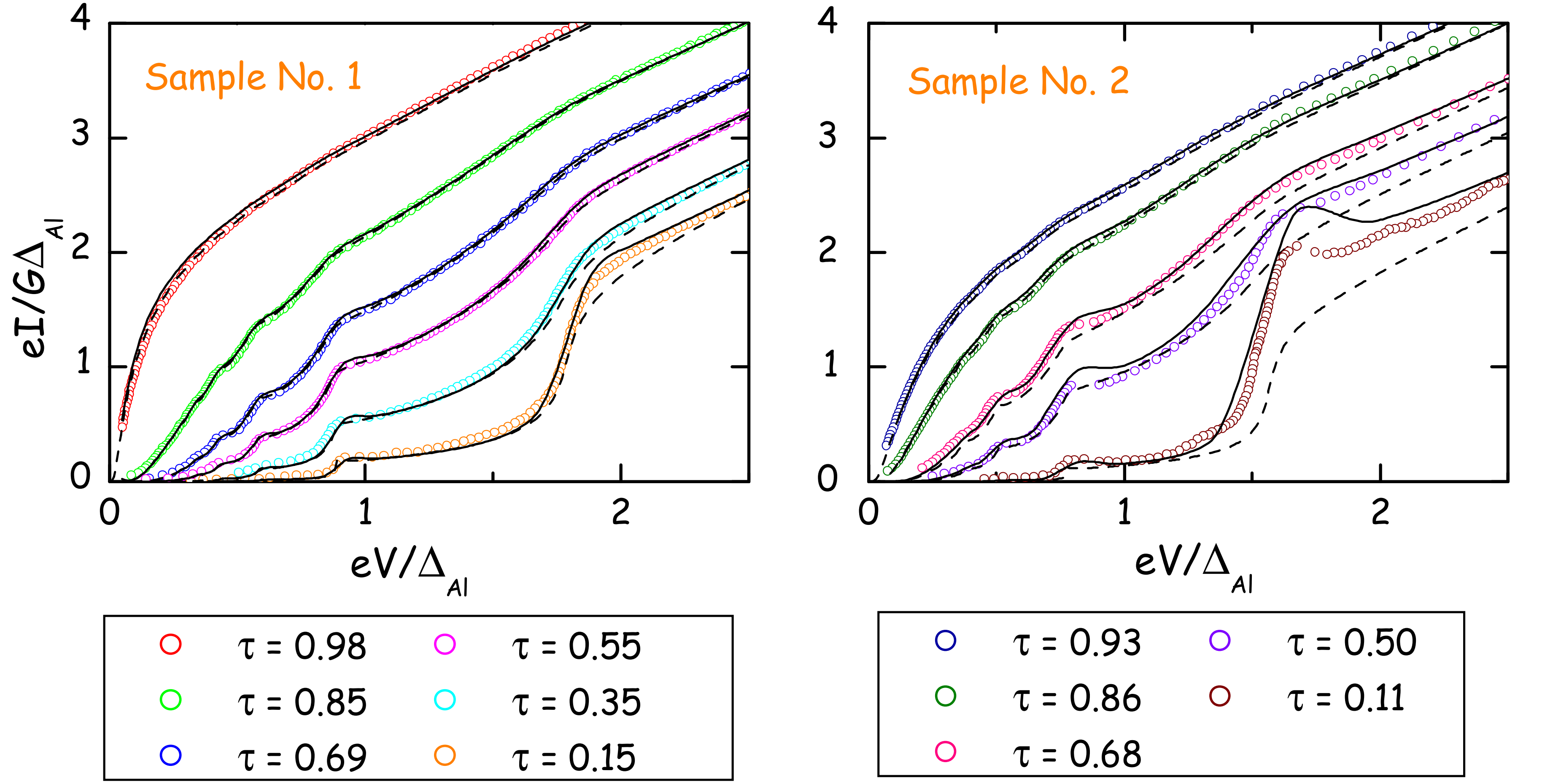
- total transmission D: $$D = \sum_{i=1}^{N} \tau_i$$

E. Scheer et al., PRL 1997

Single-atom contacts of aluminum



Single-atom contacts of gold



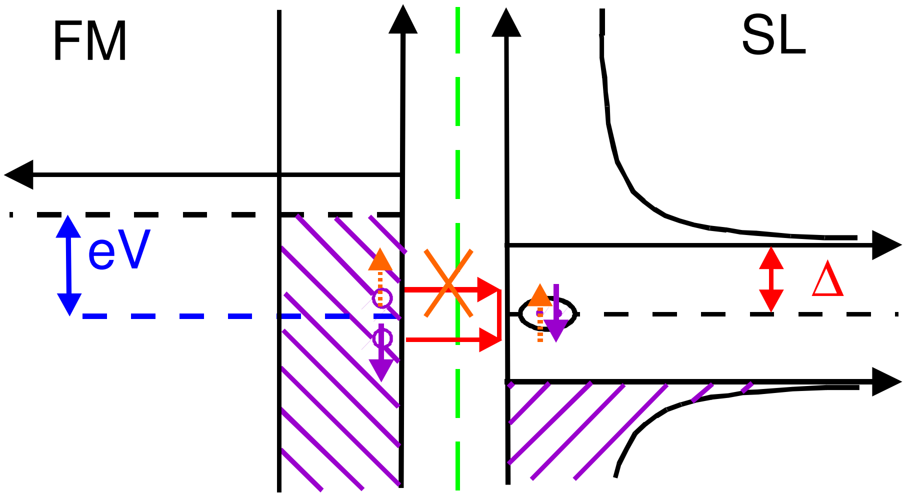
Symbols: experimental data at T < 100 mK

——— Single channel calculation with PE model

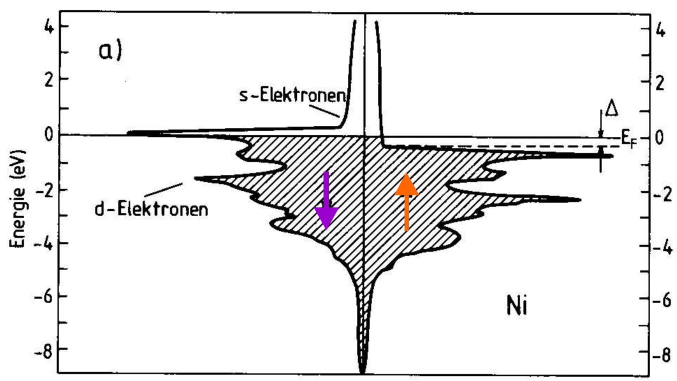
- - - - - Single channel calculation for BCS superconductor

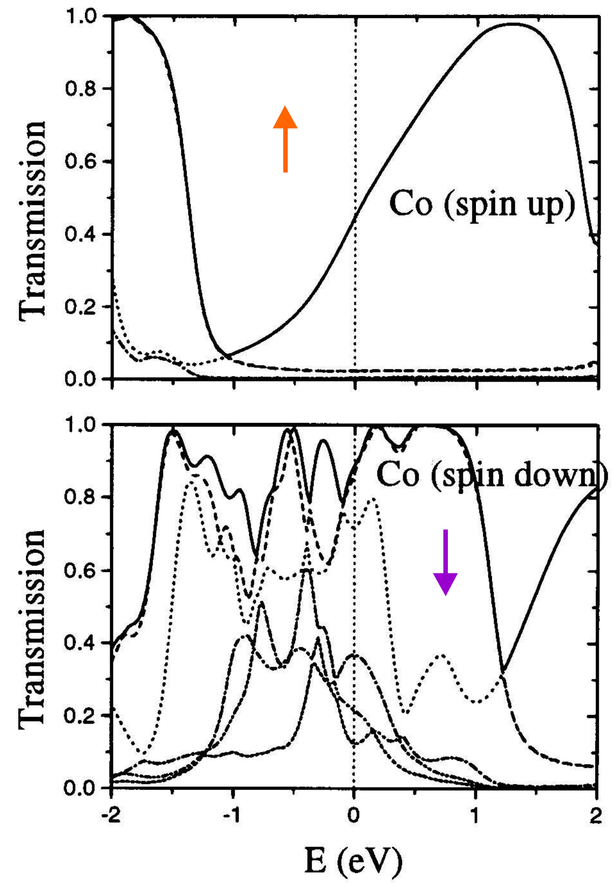
E. Scheer et al., PRL 2001

Andreev Reflection Ferro-Supra



Suppression of AR due to spin polarization

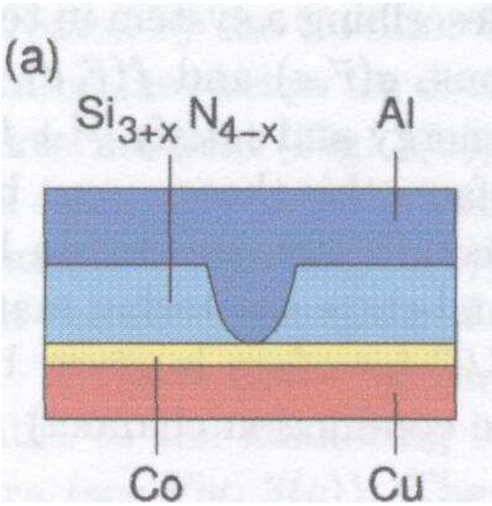




DOS of Ni
(after Callaway & Wang)

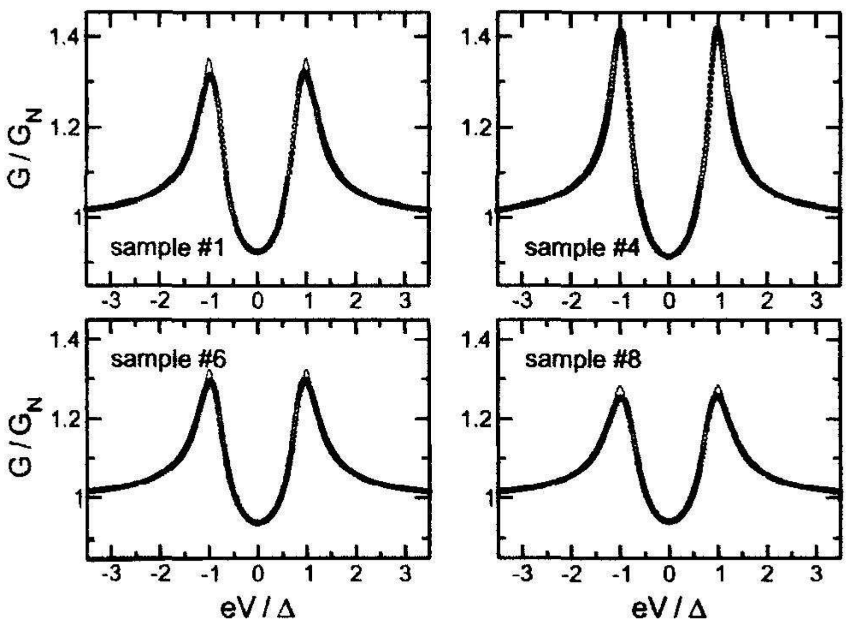
Channels of a Co single-atom contact (J.C.Cuevas, prelim.)

Measurement of spin polarization



Perez-Willard et al, PRB 2003

See also: Soulen et al, Science 1999

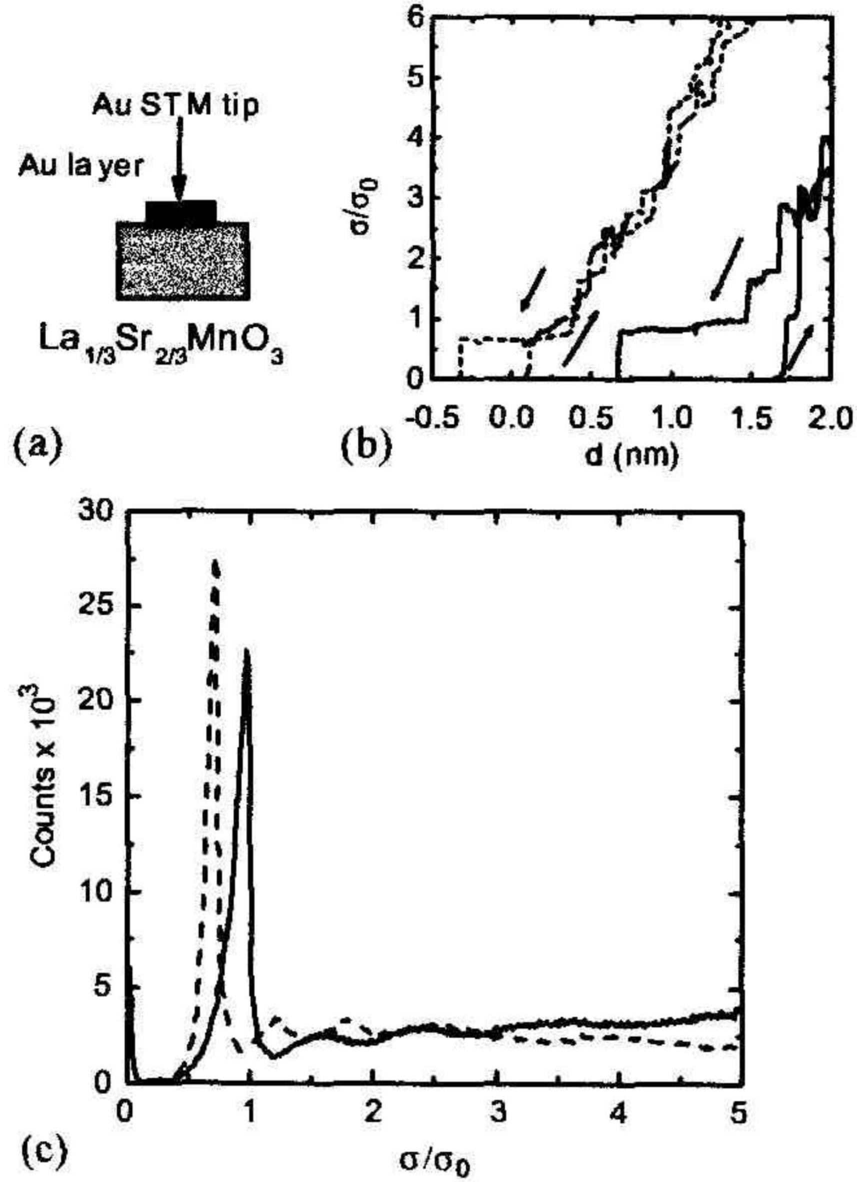


sample	d_{Co} (nm)	R_N (Ω)	T (mK)	Δ (μeV)	$\tau_\uparrow$	$\tau_\downarrow$	P
#1	6	10.4	97	189	0.404	0.979	0.42
#2	6	6.69	90	199	0.403	0.979	0.42
#3	12	33.2	101	199	0.420	0.968	0.39
#4	12	13.3	100	188	0.415	0.970	0.40
#5	24	6.00	98	180	0.382	0.989	0.44
#6	24	3.58	97	193	0.399	0.983	0.42
#7	50	15.7	99	172	0.370	0.994	0.46
#8	50	3.59	97	198	0.392	0.986	0.43

TABLE I: Transmissions, $\tau_{\uparrow,\downarrow}$, polarization, P, and gap, Δ, for the Al/Co samples as determined by a fit of the Andreev spectra for $T \approx 100$ mK with our model.

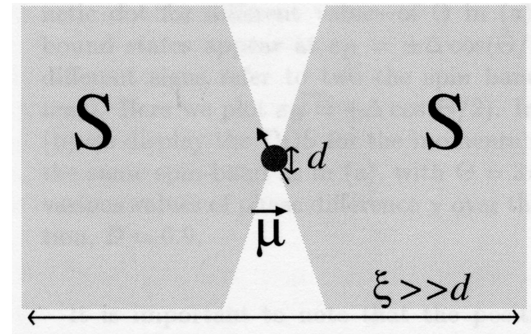
Spin polarization in atomic contacts

Change of conductance observed when using spin polarized electrode without changing the contact material



Suderow et al., 2002

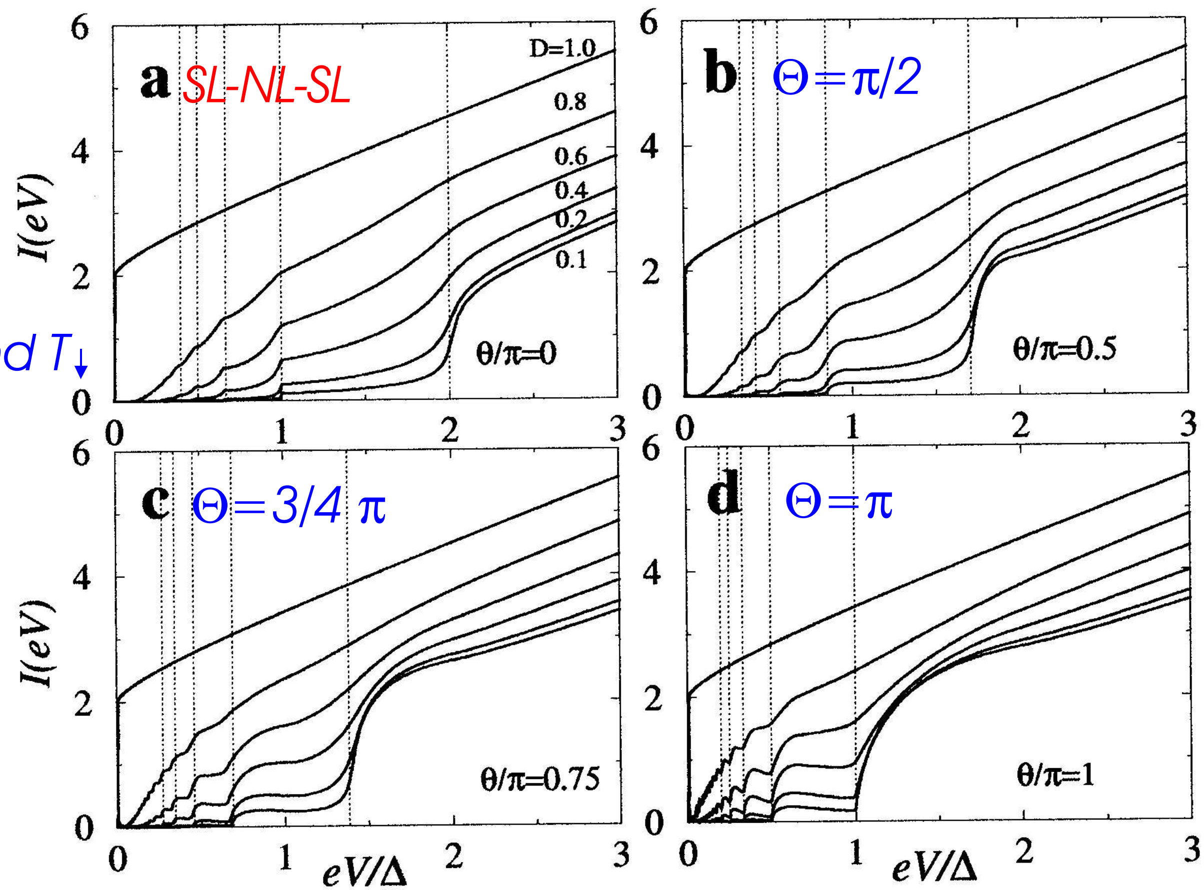
IVS OF A FM DOT WITH A SINGLE CHANNEL BETWEEN SL CONTACTS



$\Theta = \Theta(E_{ex}, d)$:
spin-mixing angle
phase between $T_\uparrow$ and $T_\downarrow$

Resonances in the DOS at
$\varepsilon_B = +/- \Delta \cos(\Theta/2)$

assumption: $T_\uparrow = T_\downarrow$



Andersson et al., Physica C 367, 117 (2002)

IVs OF SFS CONTACTS WITH A SINGLE CHANNEL PER SPIN DIRECTION

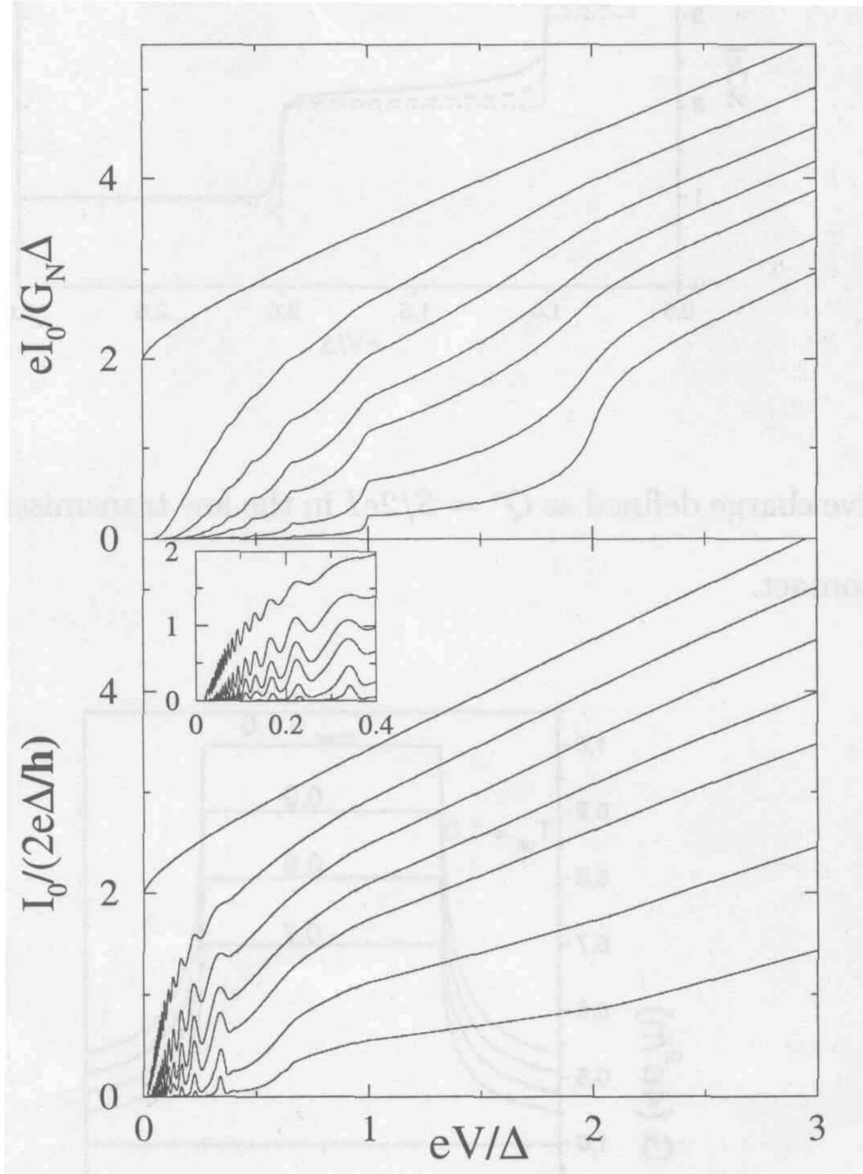
$T_\uparrow = T_\downarrow$
1.0
0.9
0.8
0.7
0.6
0.4
0.2

S-N-S
$eV=2\Delta/m$

$T_\uparrow = 1$
$T_\downarrow =$
1.0
0.9
0.8
0.7
0.6
0.4
0.2

S-F-S
$eV=\Delta/2^{1/2}m$

A. Martin-Rodero et al, Physica C 352, 67 (2001)



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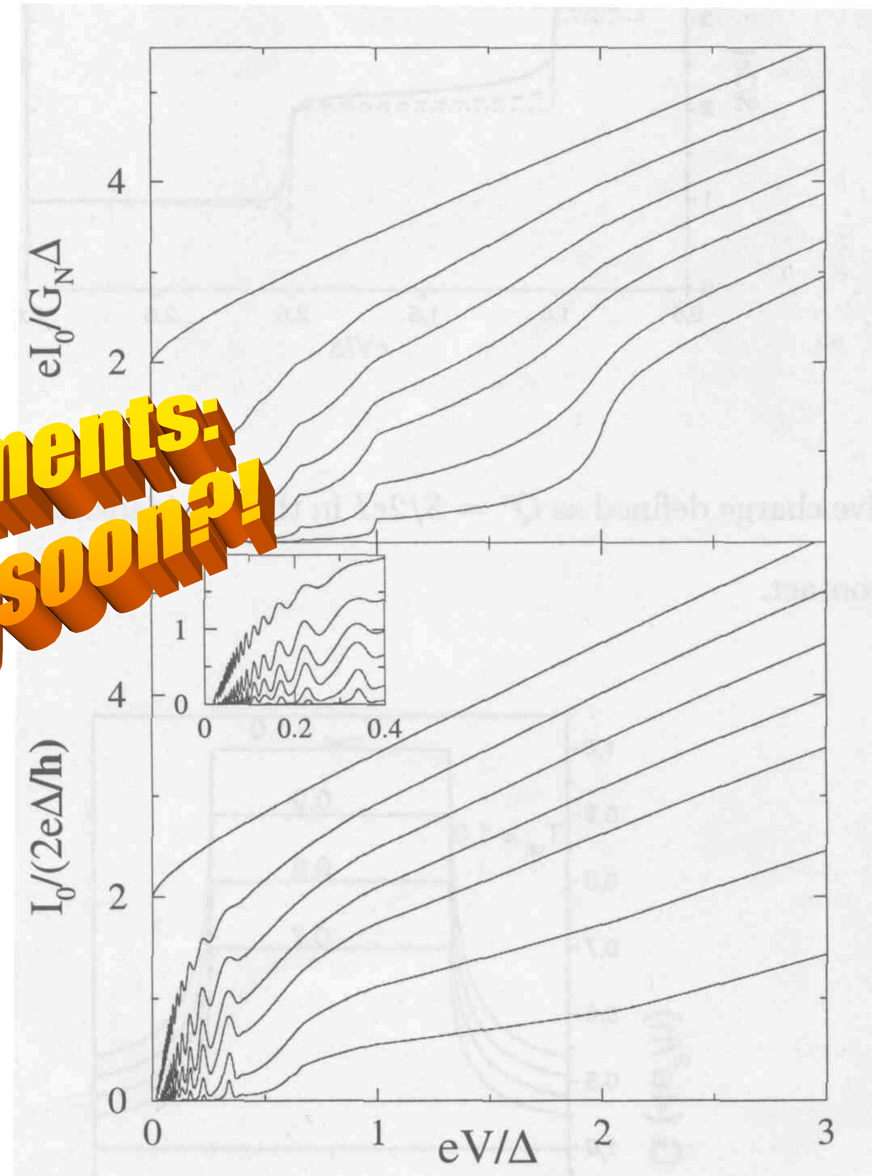
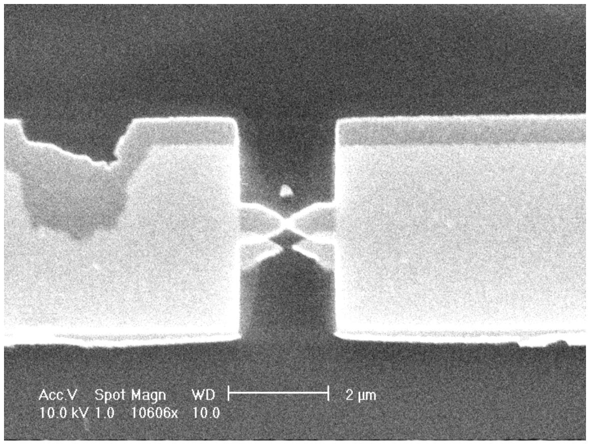
Experiments: coming soon?!

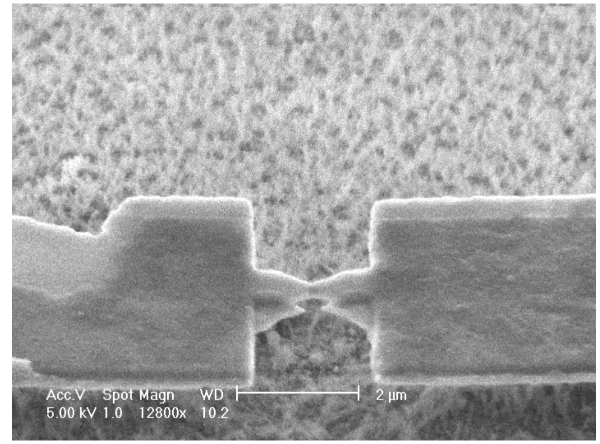


A. Martin-Rodero et al, Physica C 352, 67 (2001)

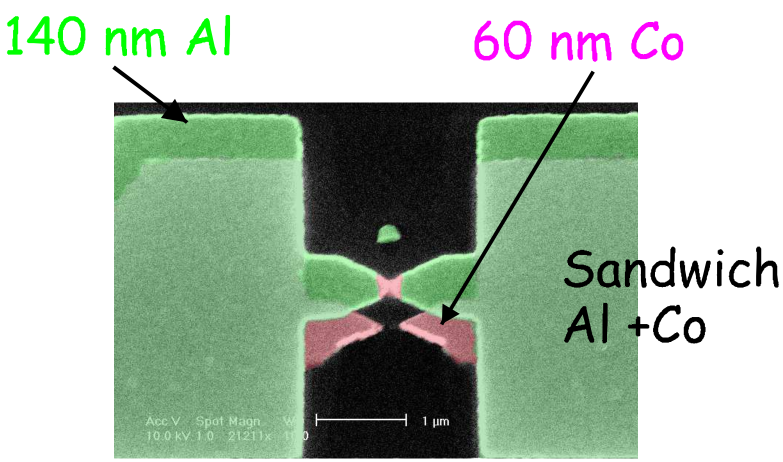
Superconductor-ferromagnet-superconductor samples



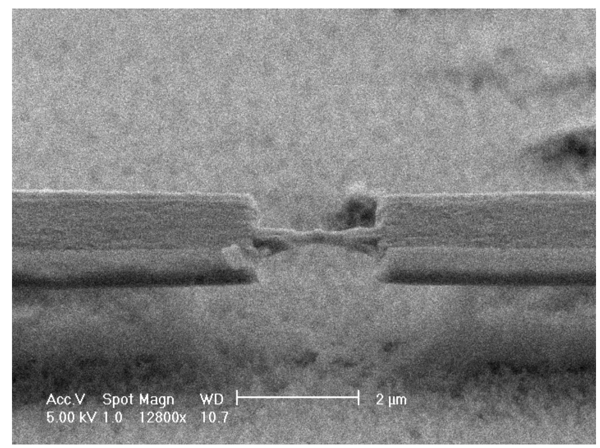
Top view after lift-off



Top view after RIE



Principle



Side view

IVs OF SFS CONTACTS WITH A SINGLE CHANNEL PER SPIN DIRECTION

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S-N-S

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Experiments: coming soon?!

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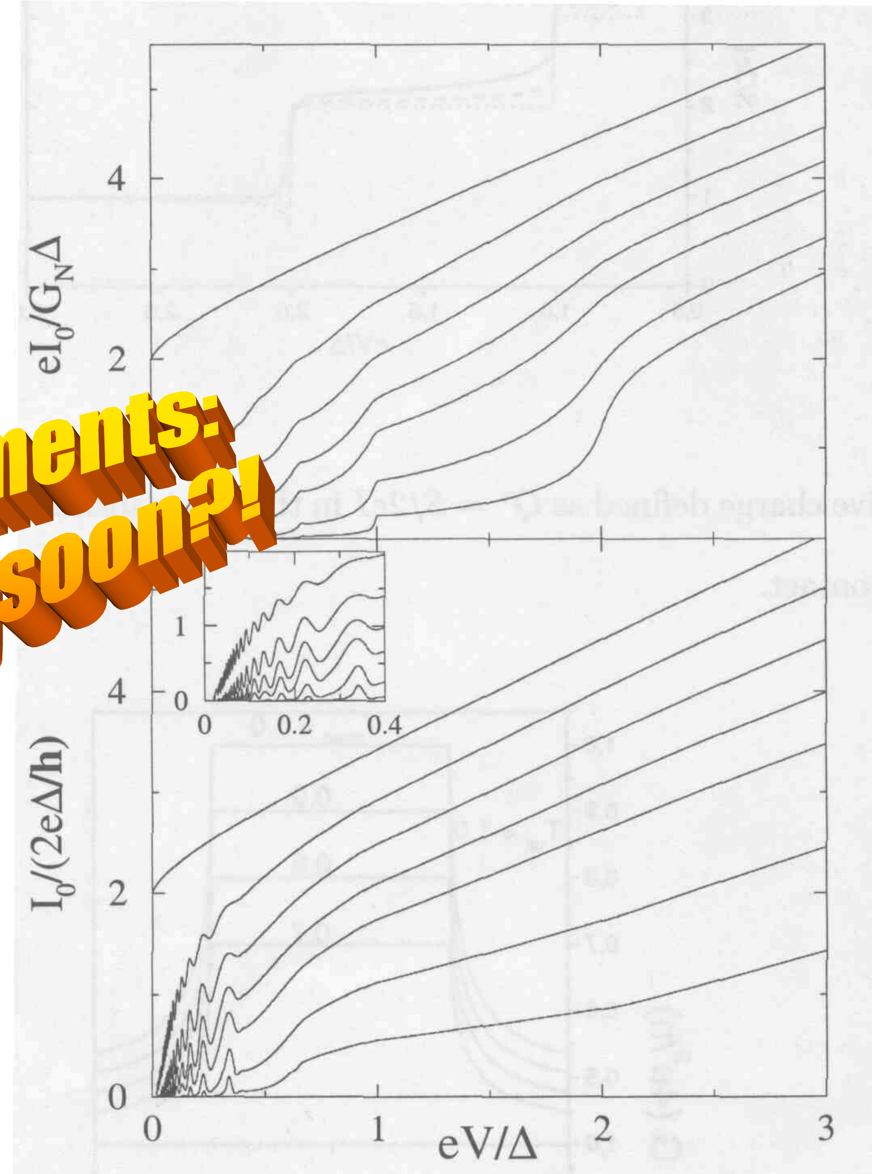

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- Micromagnetism seems to dominate the transport properties

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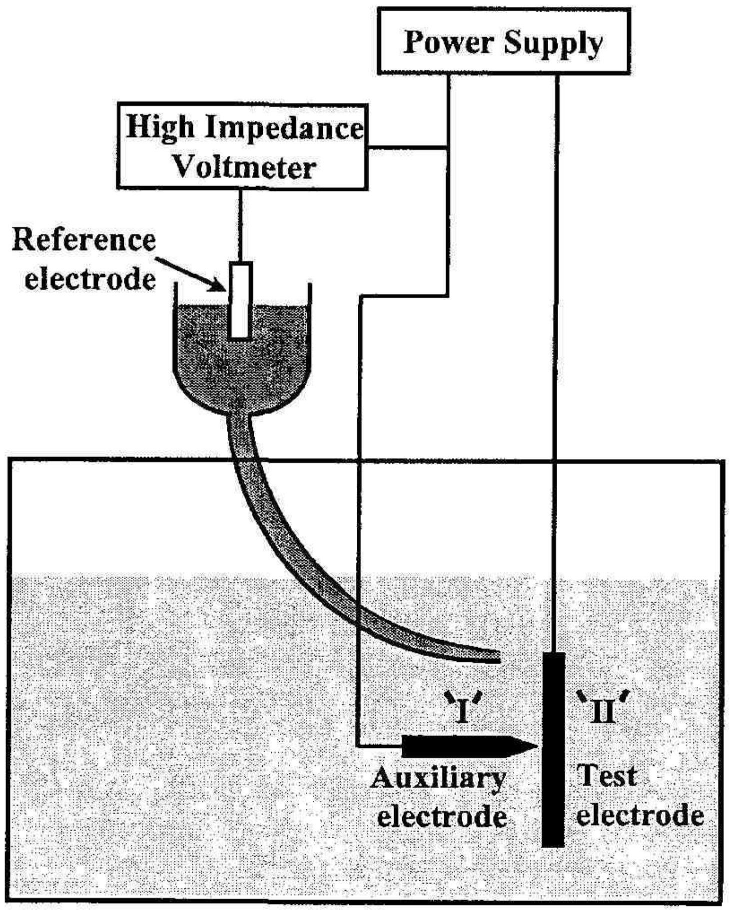
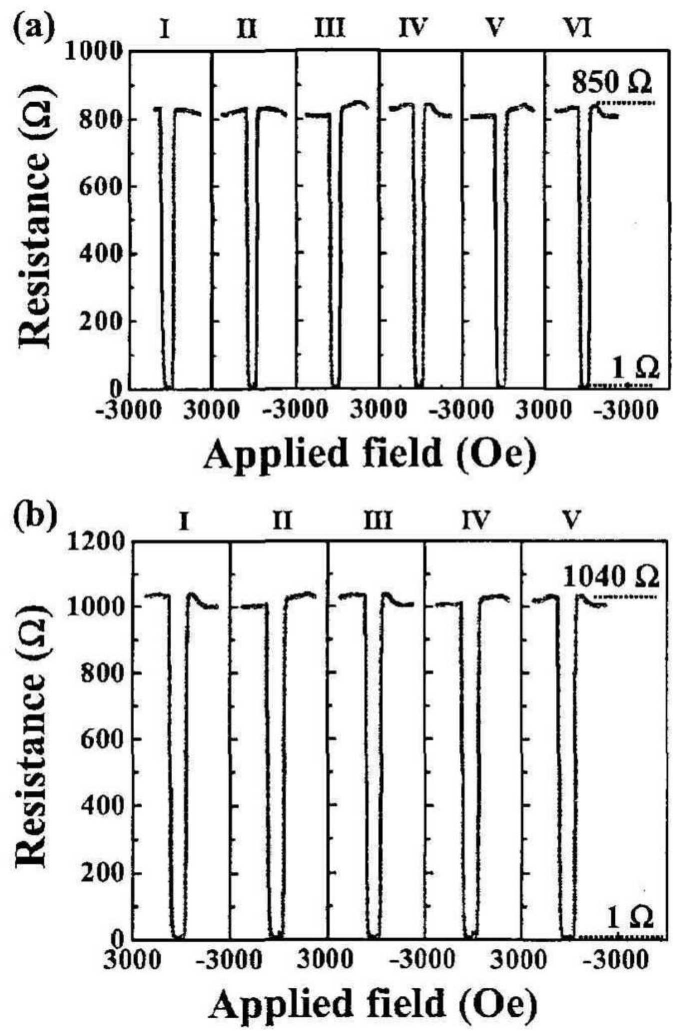
(Still) open questions:

- Origin of high MR?
- Channels of magnetic metals?
- Spin polarized channels?

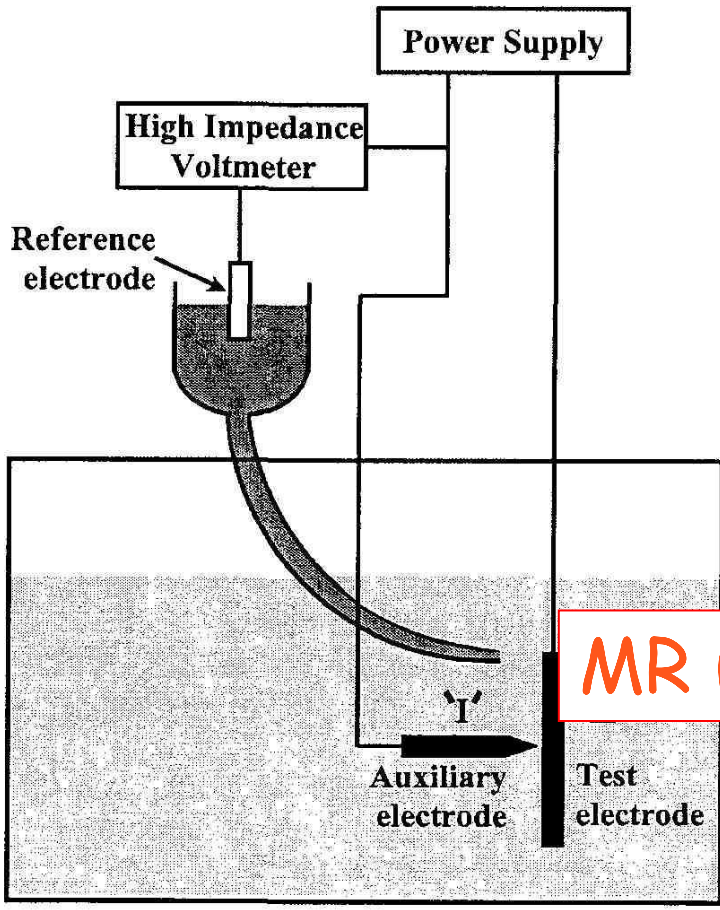
Magnetoresistance of ferromagnetic atomic contacts

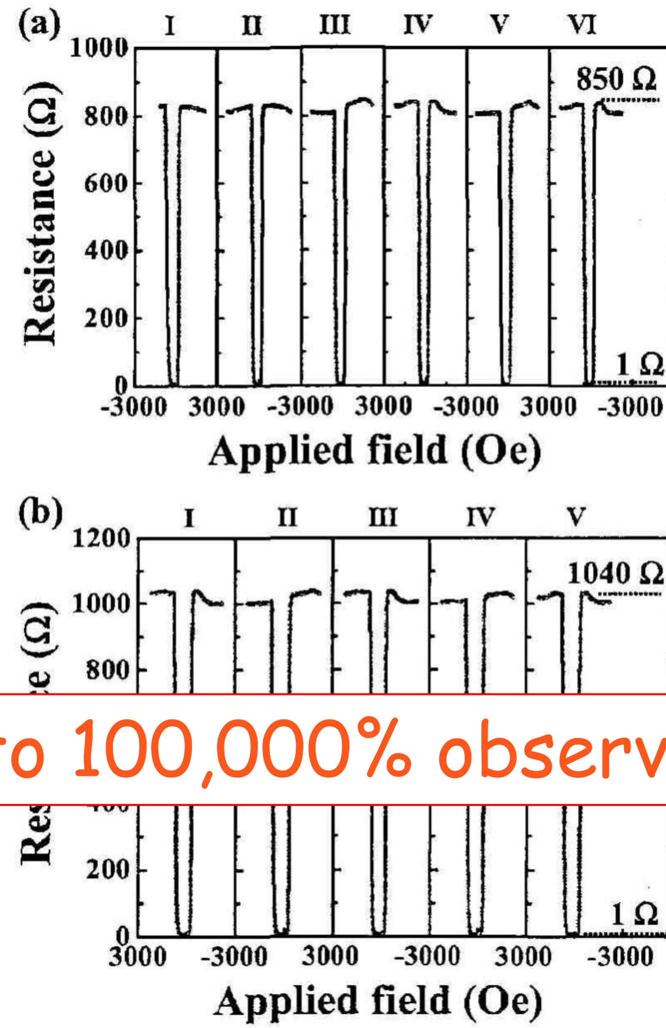




Chopra et al., 2000 ff

Magnetoresistance of ferromagnetic atomic contacts

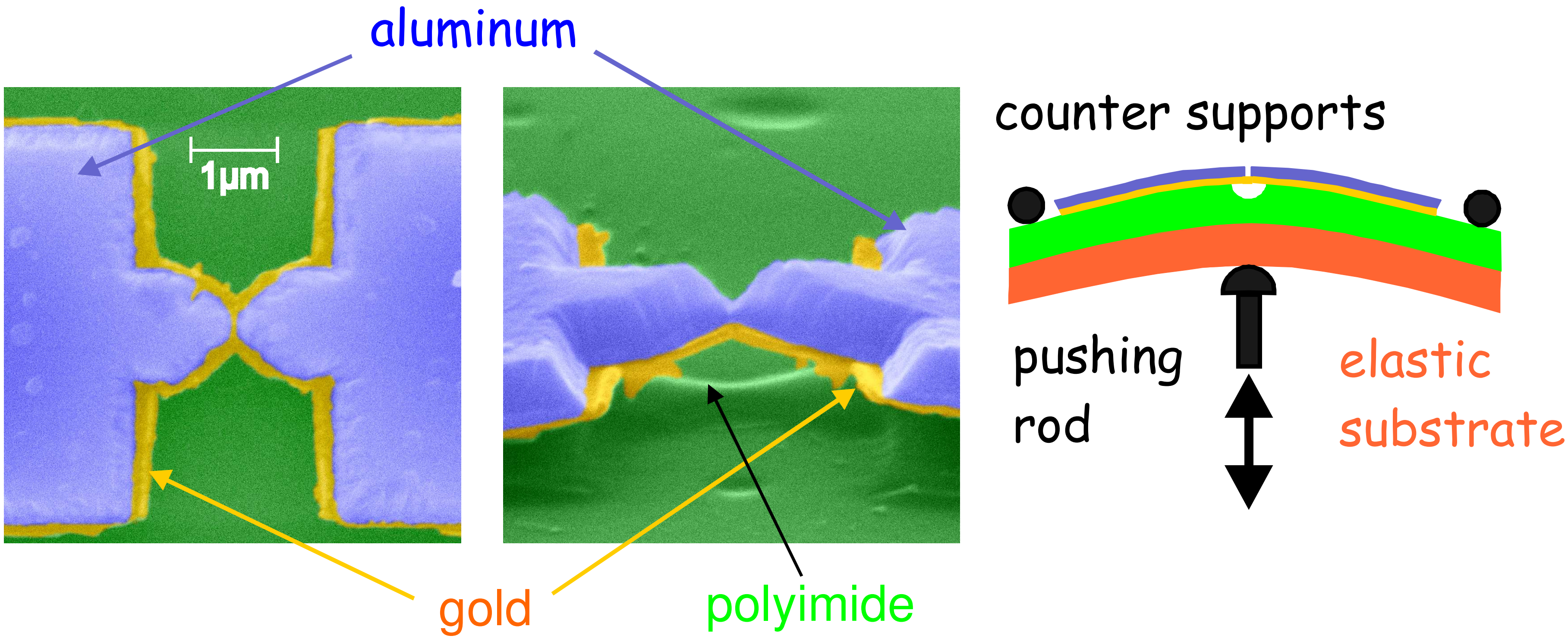




MR up to 100,000% observed!

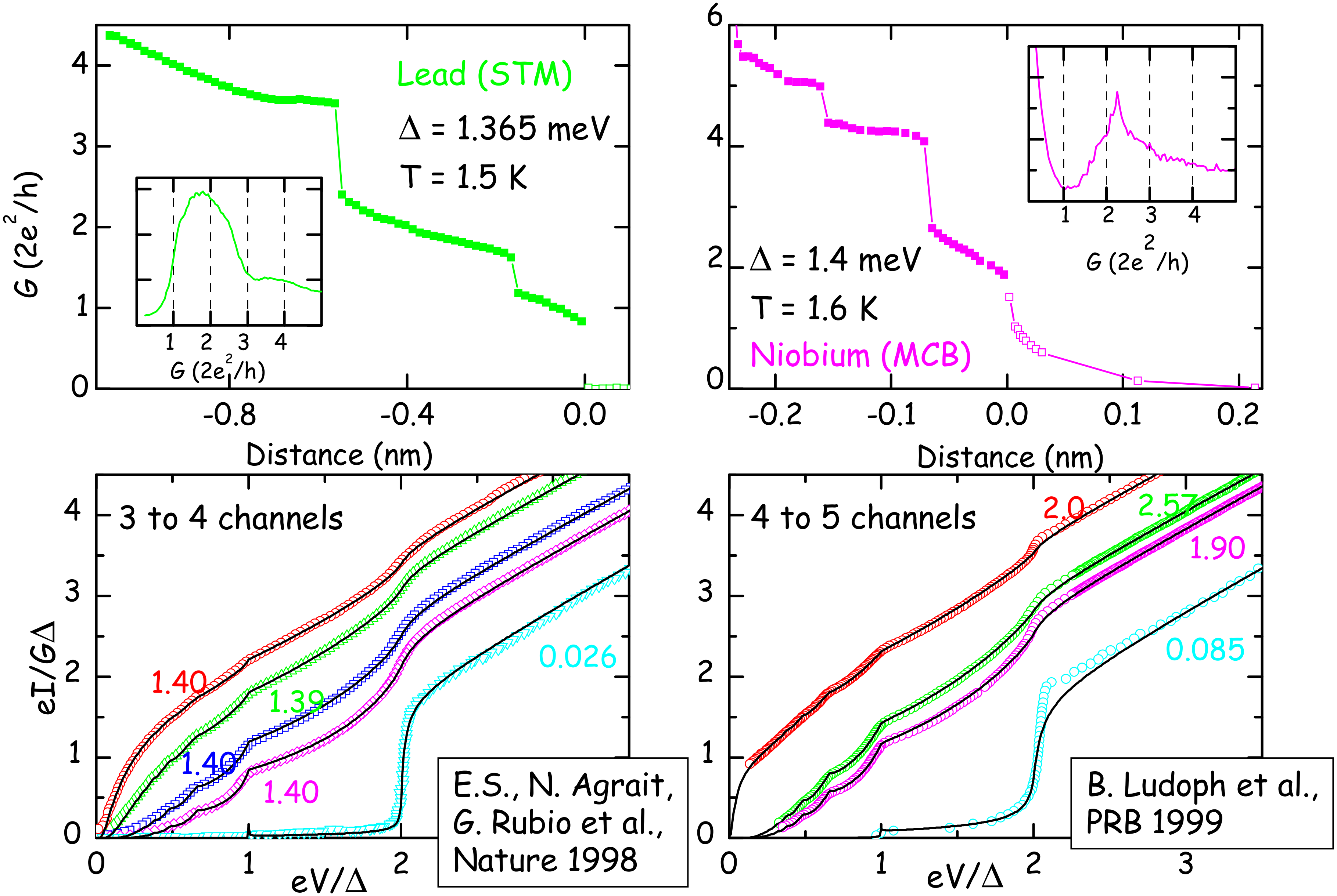
Chopra et al., 2000 ff

Superconducting gold by proximity effect

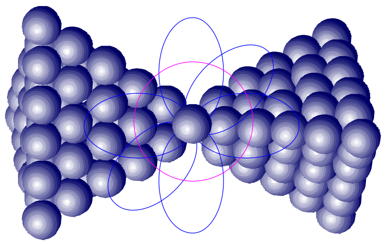


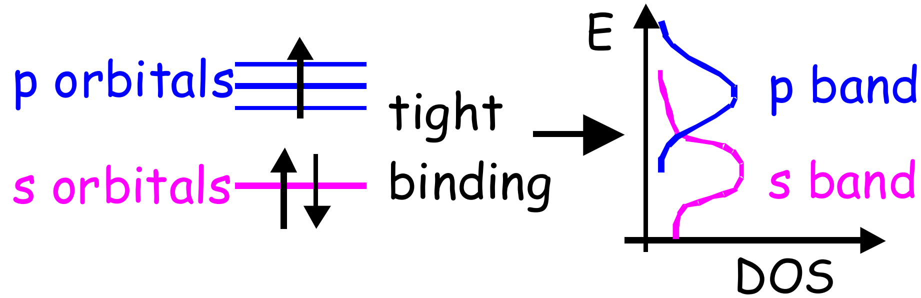
thickness of aluminum leads ~ 400 nm
thickness of gold layer ~ 30 nm
gap width between leads ~ 50 nm

Single-atom contacts of lead and niobium



Localized orbitals model for sp metals



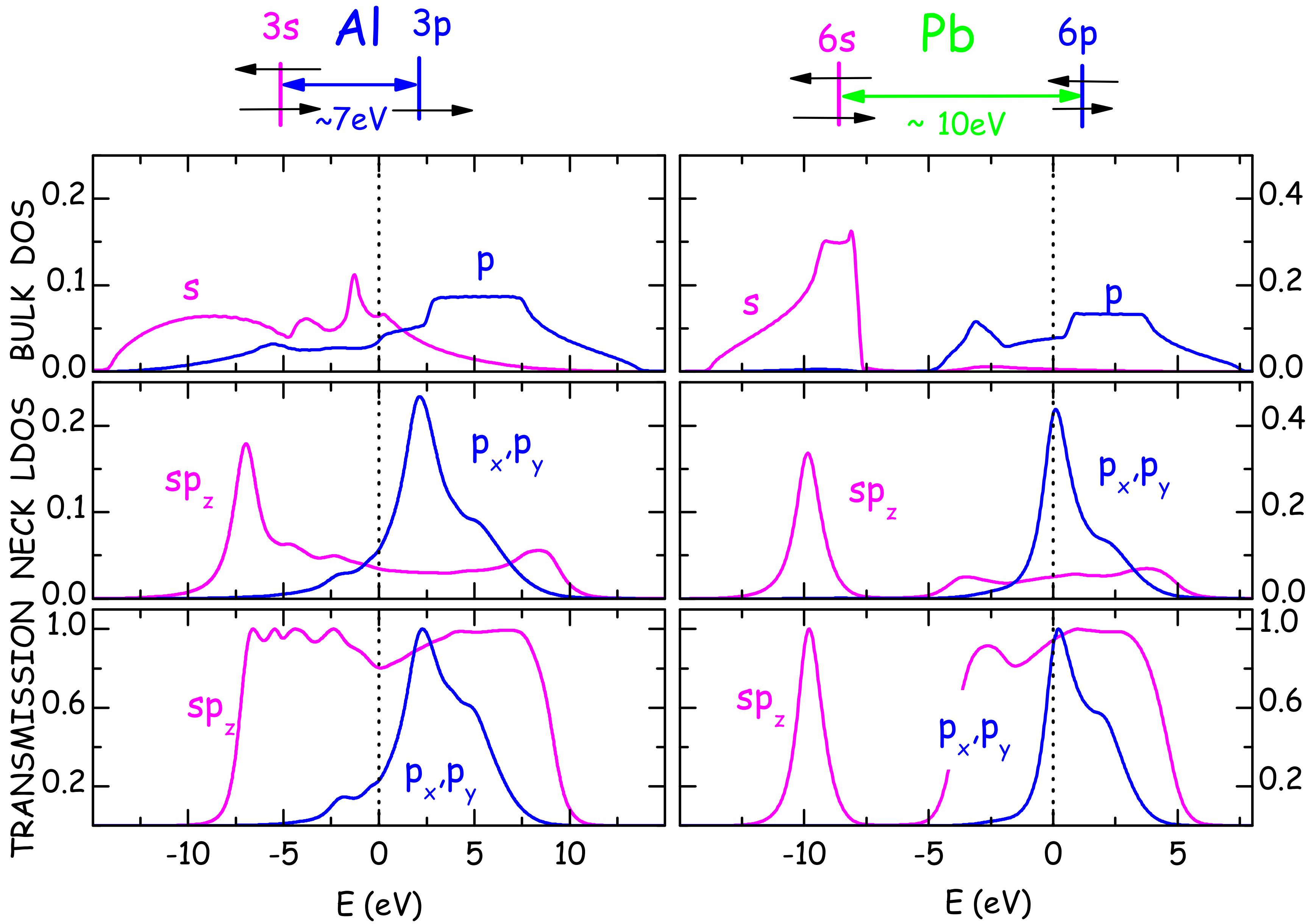


Maximum number of transport channels	=	number of valence orbitals	≥	number of active channels
monovalent metals (1 s orbital), e.g. Au, Ag, Na		$N_{max} = 1$		N = 1
divalent metals (1 s + 3 p orbitals), e.g. Zn, Hg, Mg		$N_{max} = 4$		N = 2
sp-like metals (1 s + 3 p orbitals), e.g. Al, Pb		$N_{max} = 4$		N = 3-4
transition metals (1 s + 5 d orbitals) e.g. Nb, W		$N_{max} = 6$		N = 5

$\{\tau_i\}$ depends on the precise atomic arrangement and local Fermi level -> number of "active" channels is in general smaller.

Levy Yeyati et al., PRB 1997; Cuevas et al., PRL 1998; Häfner et al., tbp

Localized orbitals model for sp metals



Channels of FM single-atom contacts

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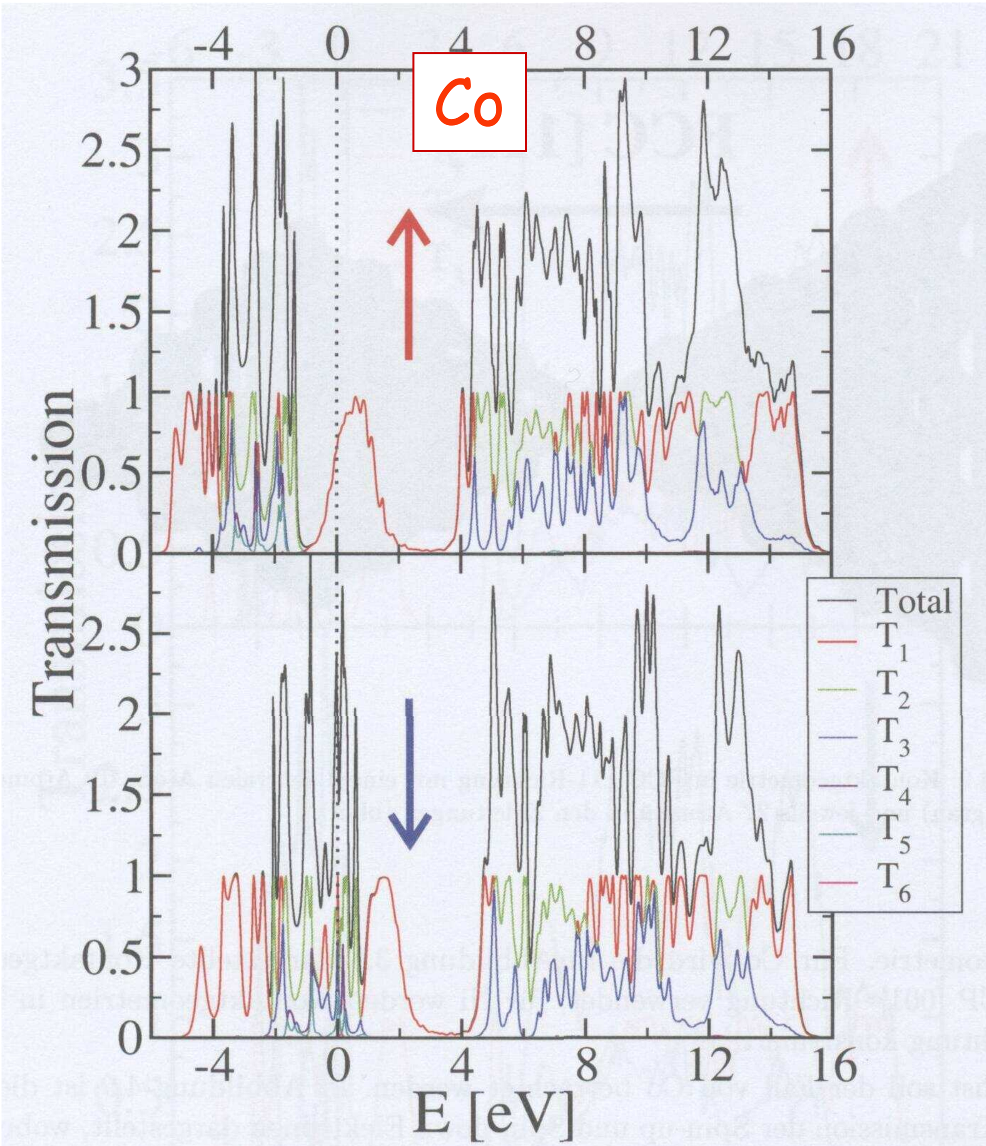

M. Häfner et al, tbp

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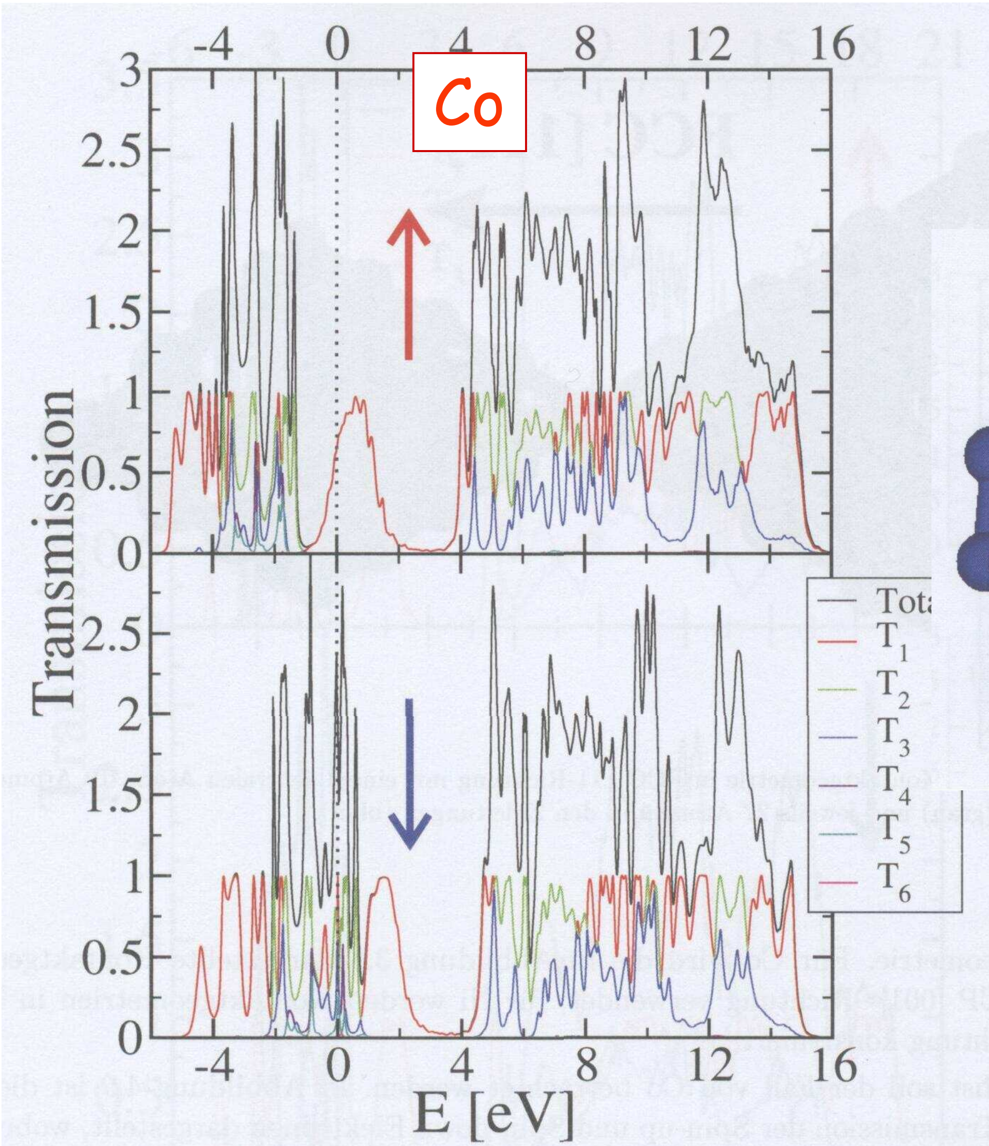

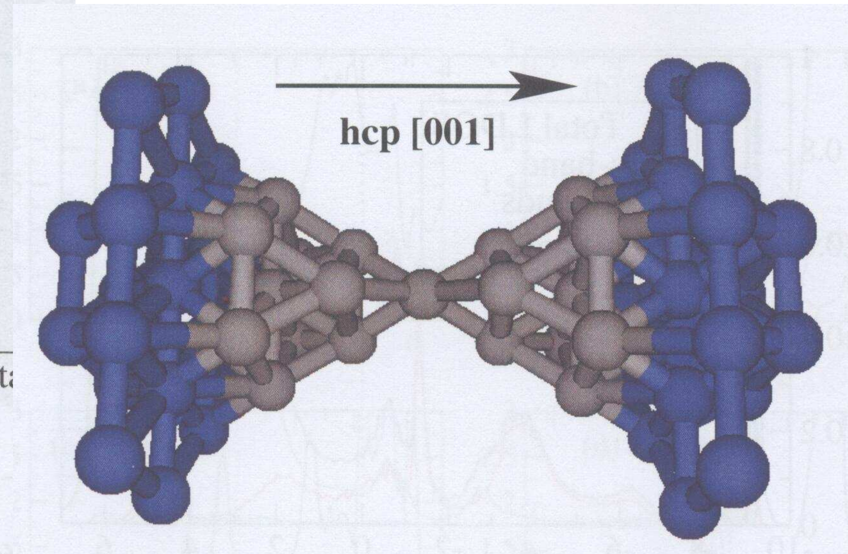

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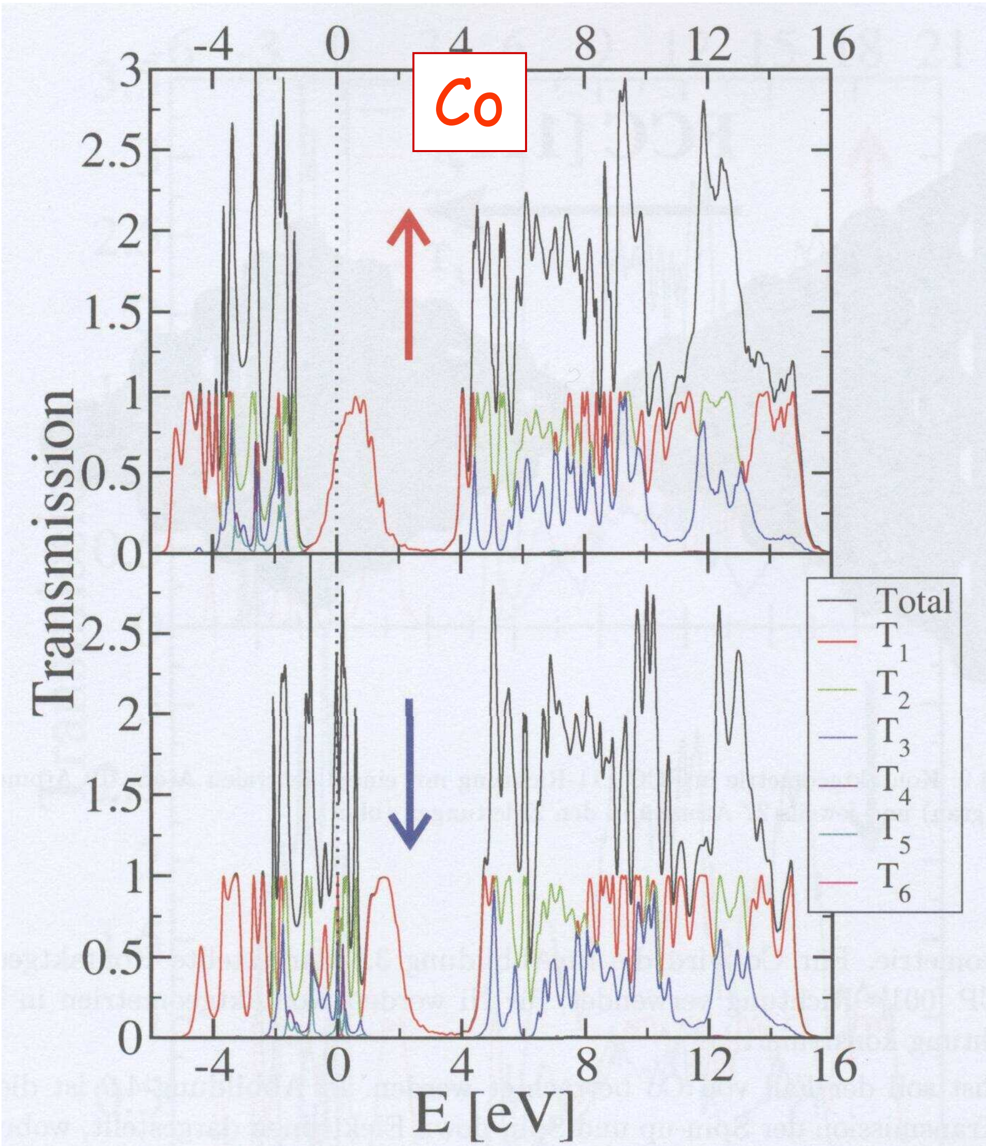

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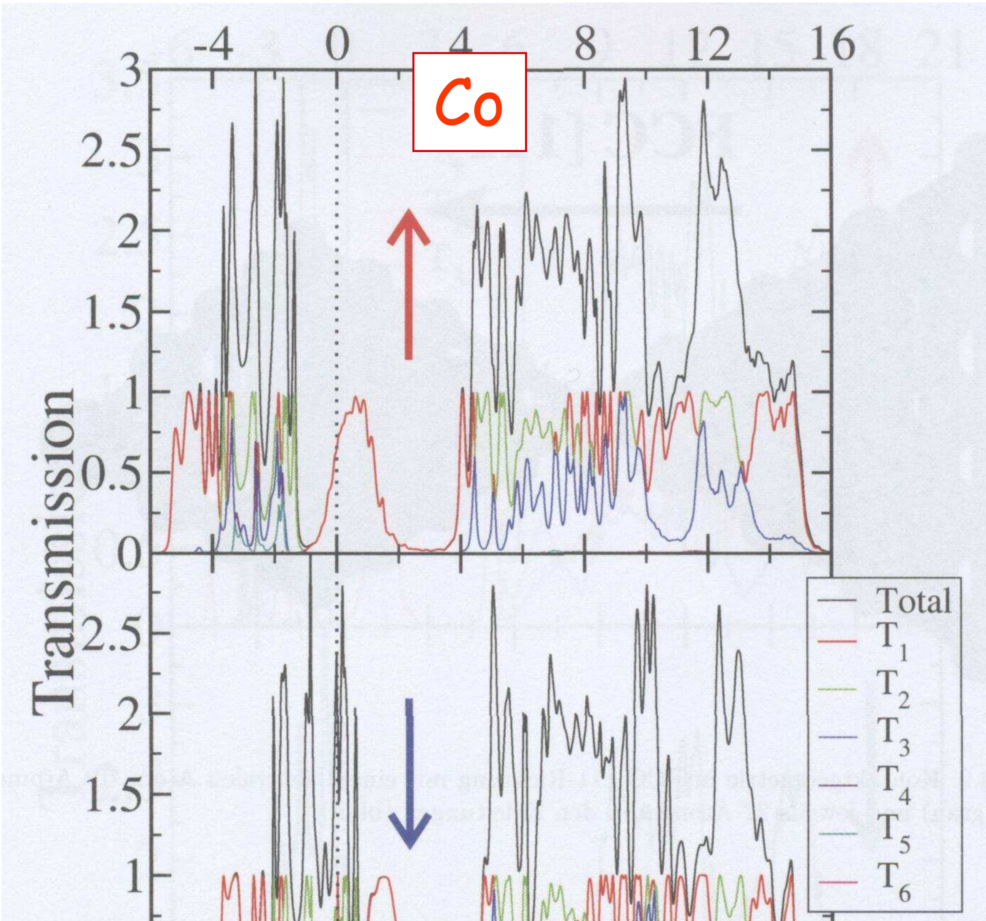
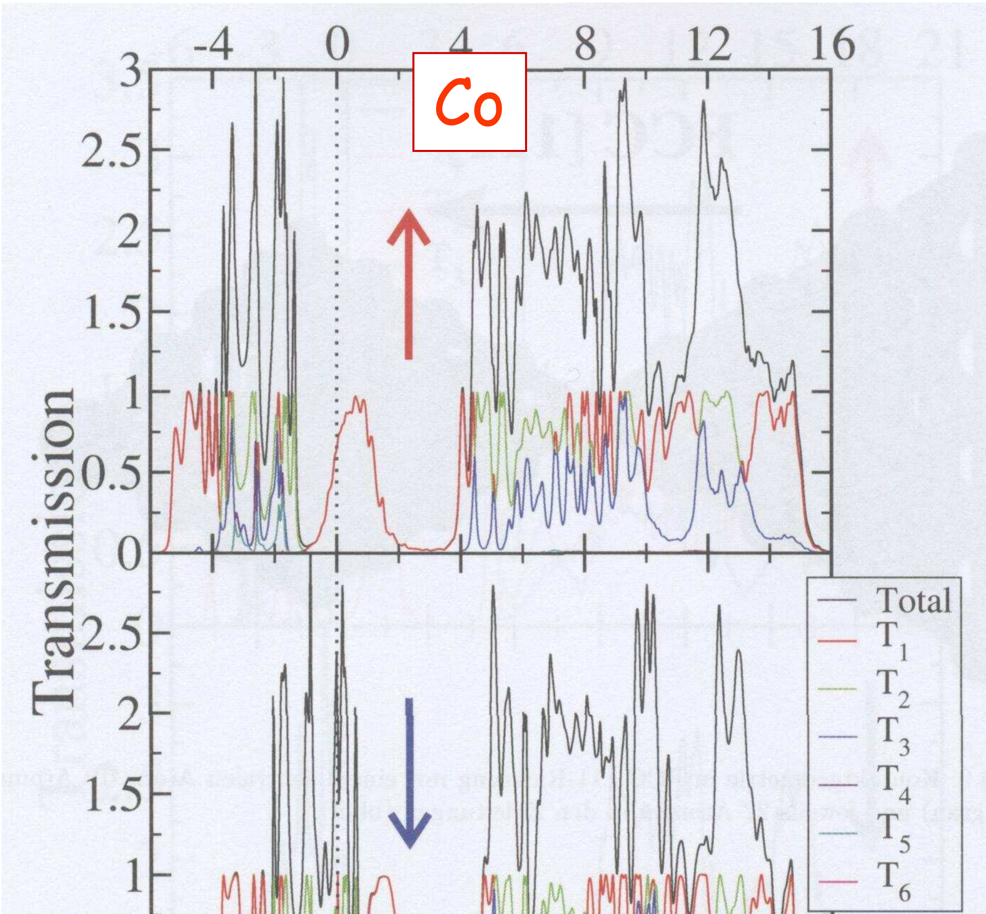


$$T_{\uparrow} = 0.64 = T_{\uparrow 1}$$

$$T_{\downarrow} = 2.37; T_{\downarrow 1} = 1, T_{\downarrow 2} = T_{\downarrow 3} = 0.48,$$

$$T_{\downarrow 4} = T_{\downarrow 5} = 0.20, P = 0.57$$

Channels of FM single-atom contacts



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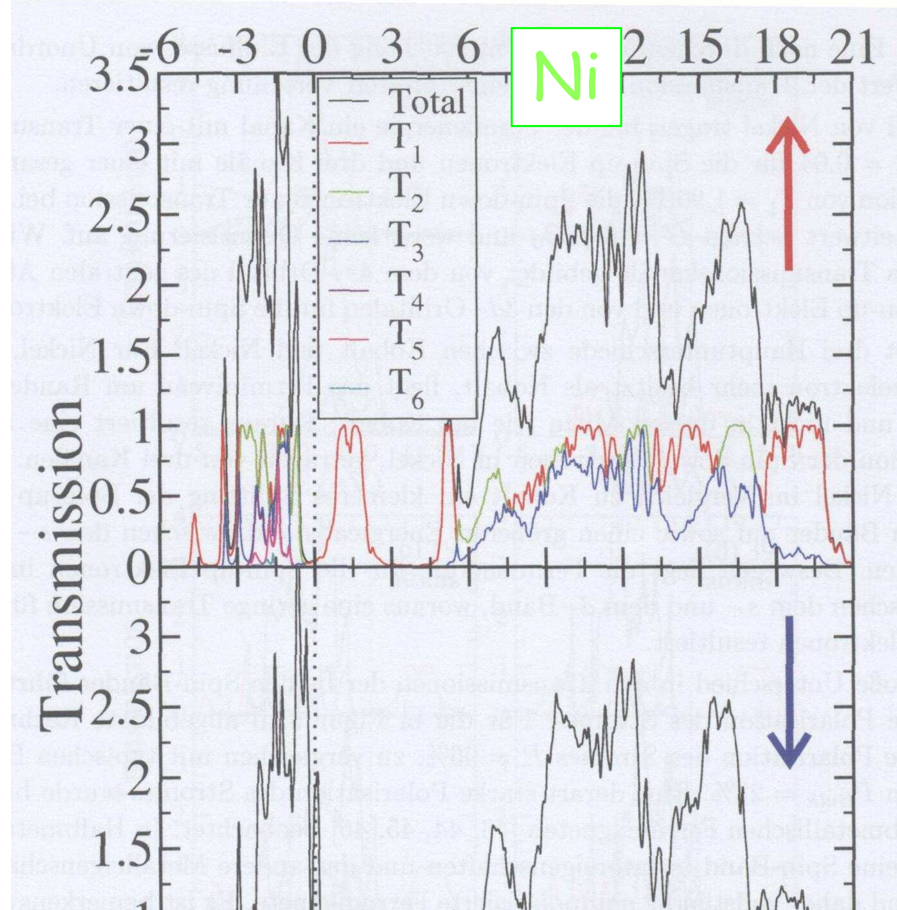
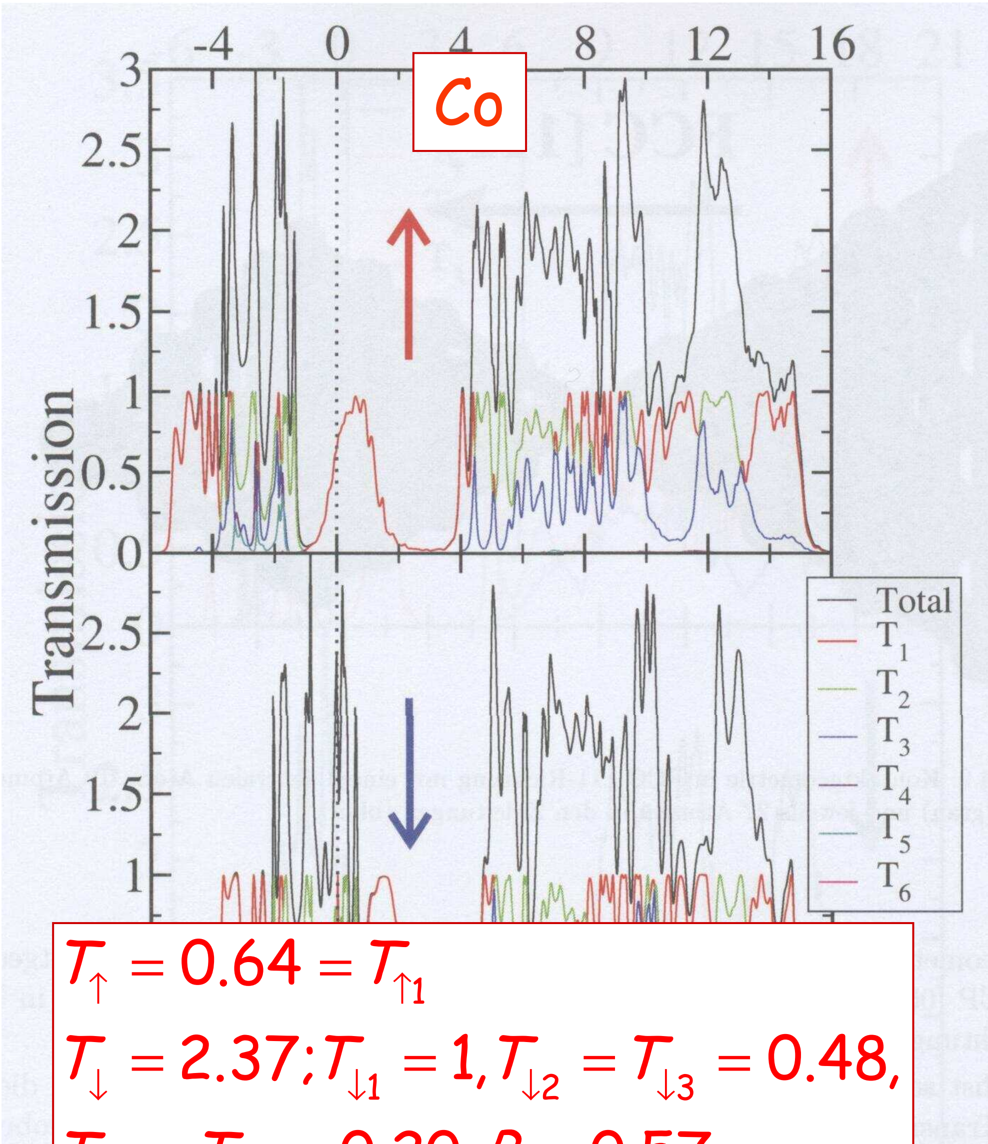


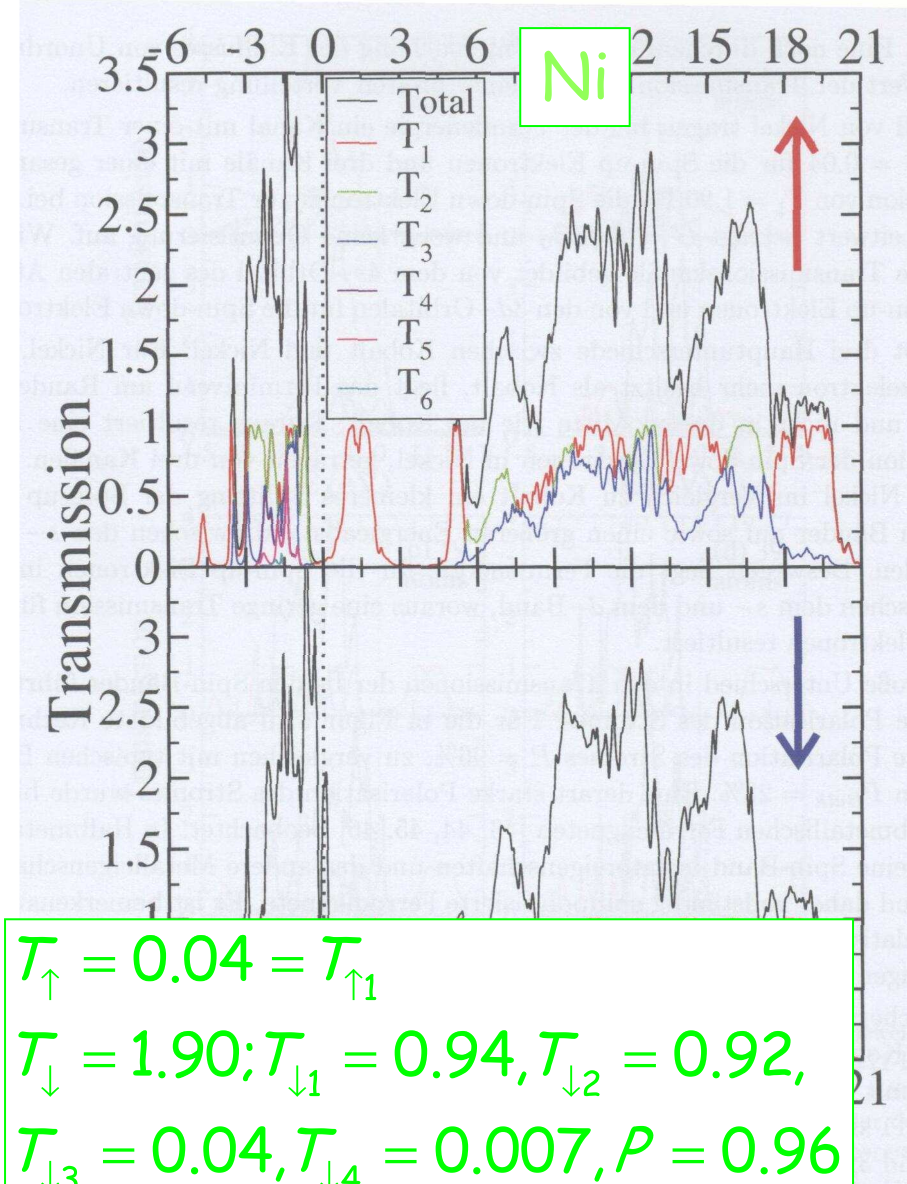
$T_{\uparrow} = 0.04 = T_{\uparrow 1}$

$T_{\downarrow} = 1.90; T_{\downarrow 1} = 0.94, T_{\downarrow 2} = 0.92,$

$T_{\downarrow 3} = 0.04, T_{\downarrow 4} = 0.007, P = 0.96$

Channels of FM single-atom contacts





$T_\uparrow = 0.64 = T_{\uparrow 1}$

$T_\downarrow = 2.37; T_{\downarrow 1} = 1, T_{\downarrow 2} = T_{\downarrow 3} = 0.48,$

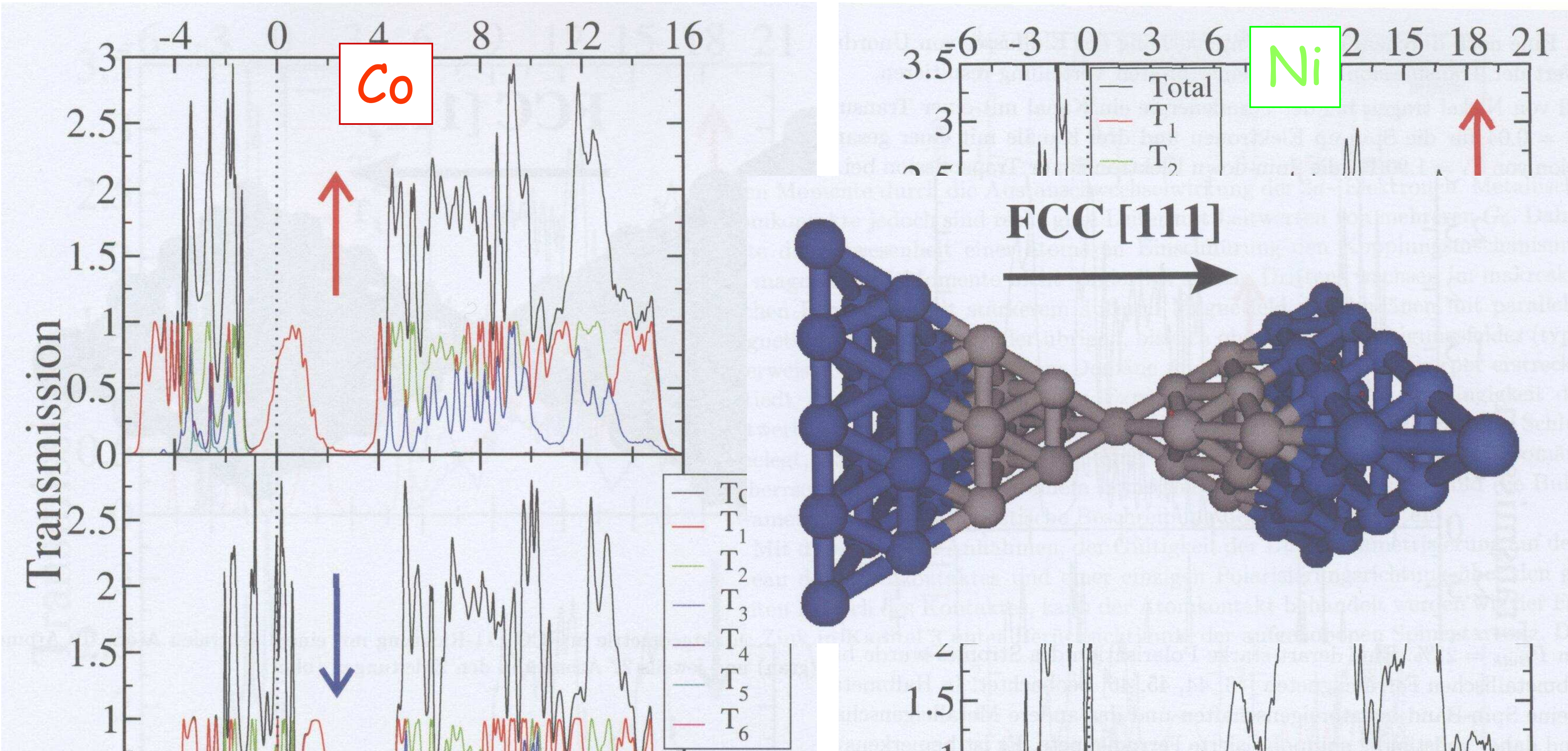
$T_{\downarrow 4} = T_{\downarrow 5} = 0.20, P = 0.57$

$T_\uparrow = 0.04 = T_{\uparrow 1}$

$T_\downarrow = 1.90; T_{\downarrow 1} = 0.94, T_{\downarrow 2} = 0.92,$

$T_{\downarrow 3} = 0.04, T_{\downarrow 4} = 0.007, P = 0.96$

Channels of FM single-atom contacts



$T_{\uparrow} = 0.64 = T_{\uparrow 1}$

$T_{\downarrow} = 2.37; T_{\downarrow 1} = 1, T_{\downarrow 2} = T_{\downarrow 3} = 0.48,$

$T_{\downarrow 4} = T_{\downarrow 5} = 0.20, P = 0.57$

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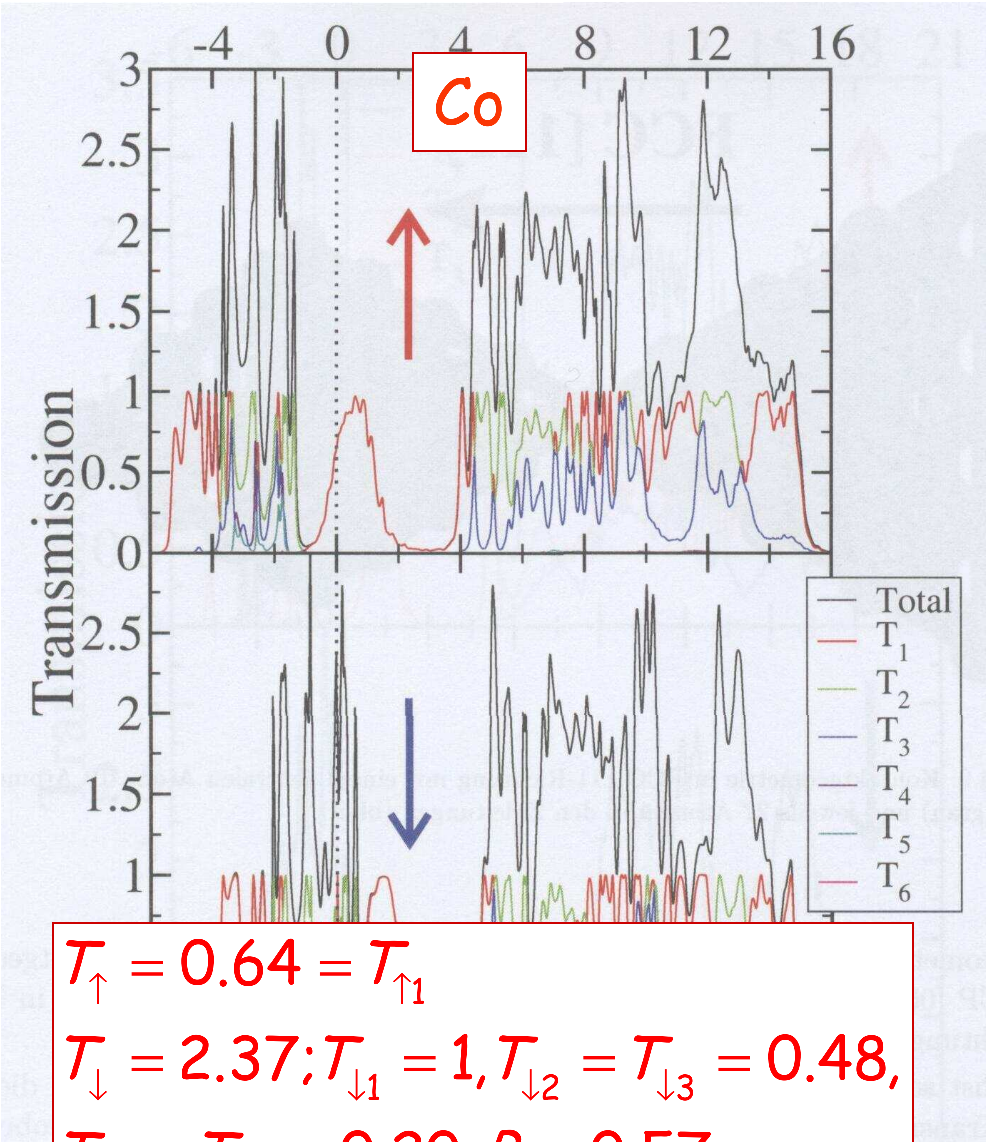
Channels of FM single-atom contacts



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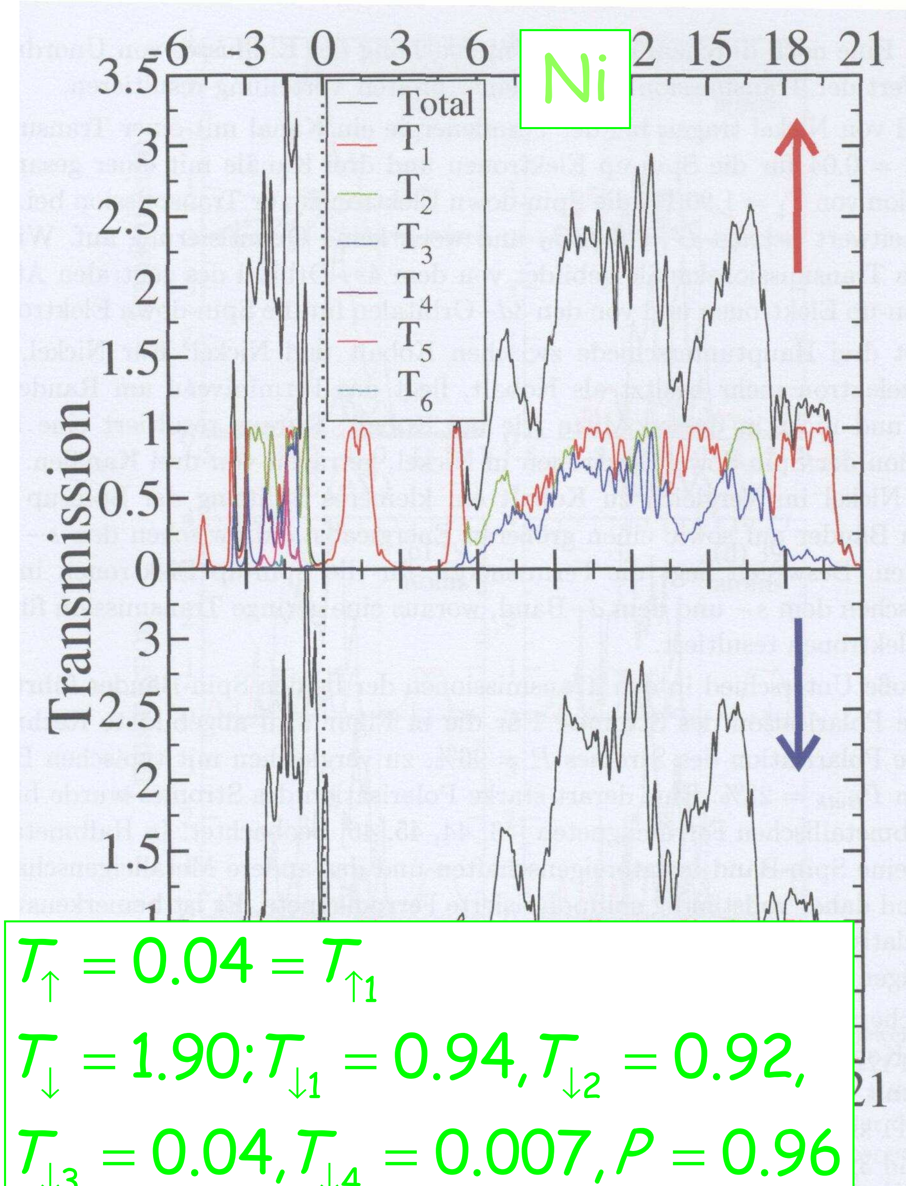

$T_{\uparrow} = 0.04 = T_{\uparrow 1}$

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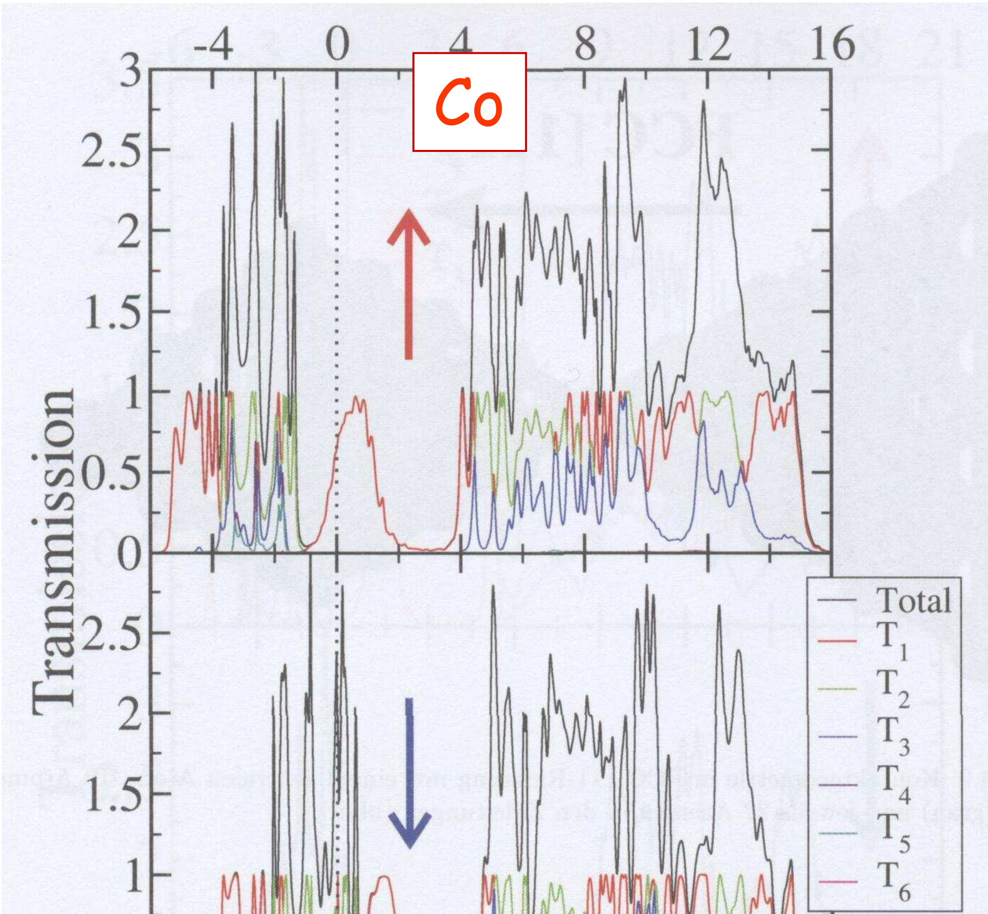
Channels of FM single-atom contacts



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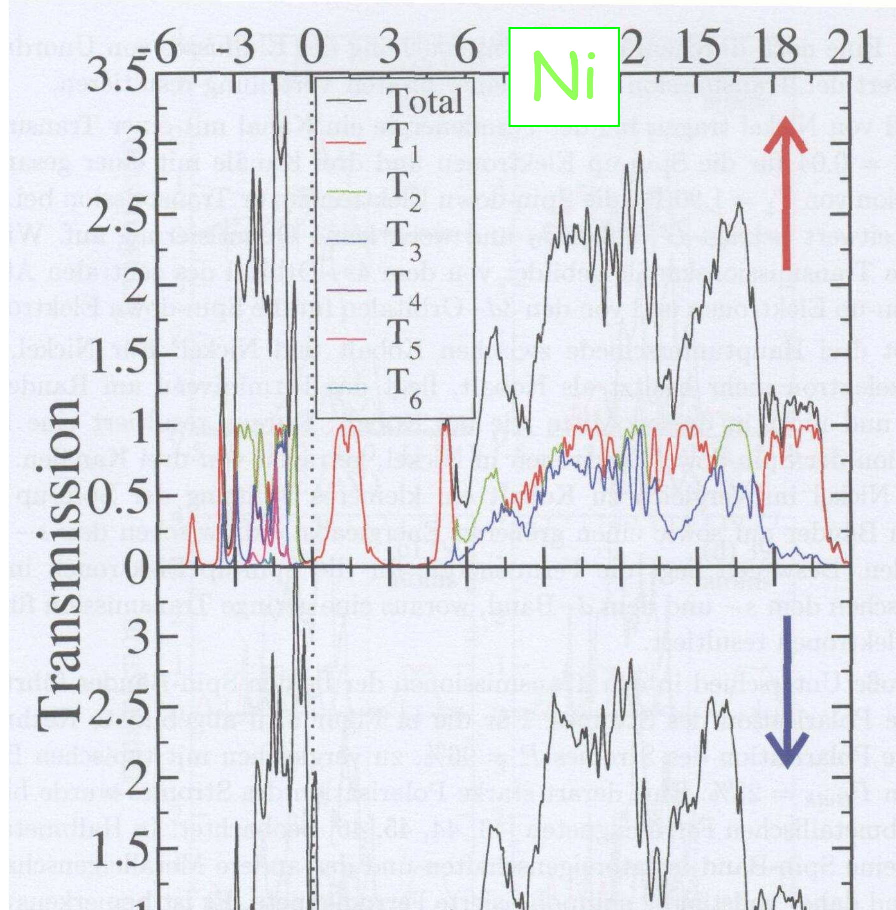

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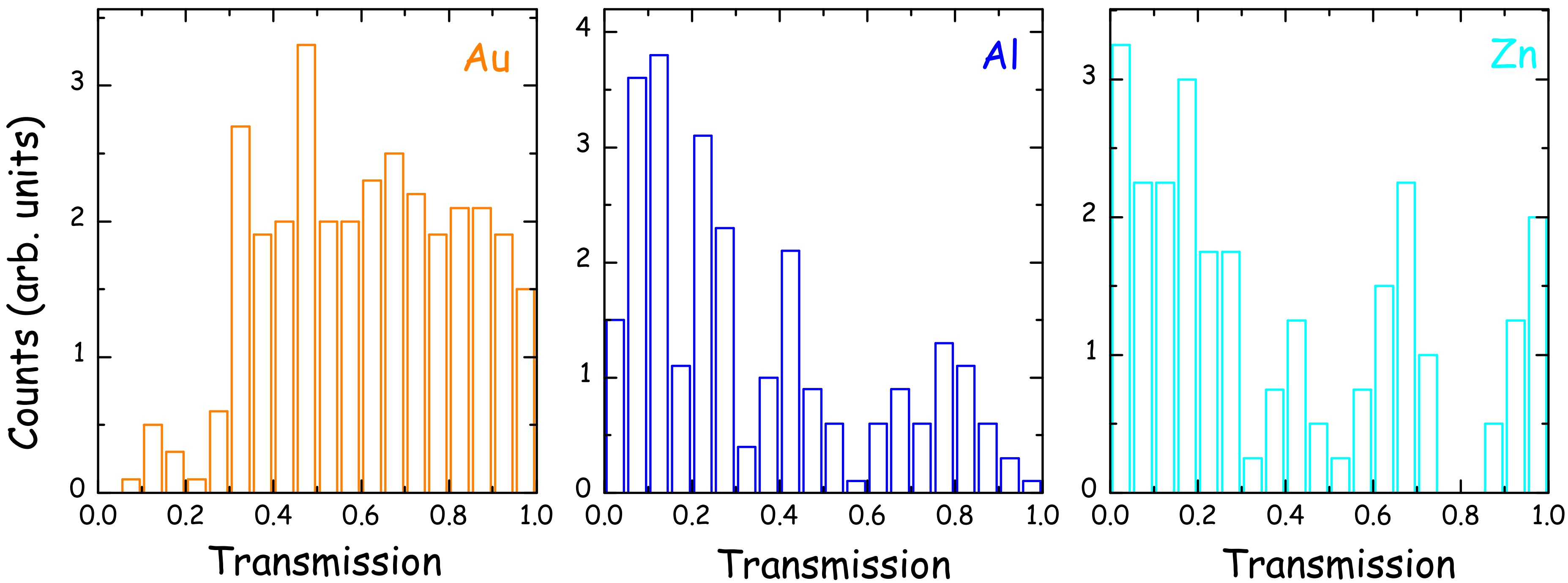
$T_{\downarrow} = 1.90; T_{\downarrow 1} = 0.94, T_{\downarrow 2} = 0.92,$

$T_{\downarrow 3} = 0.04, T_{\downarrow 4} = 0.007, P = 0.96$

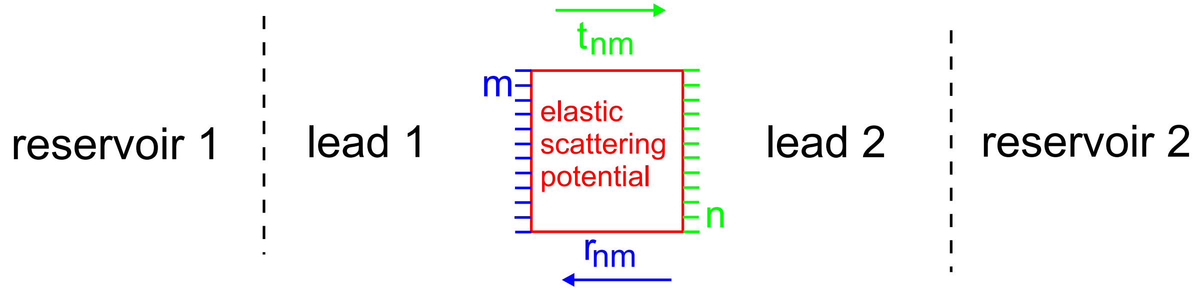
Transmission histograms



Transmission τ = 1 possible with Au and Zn

T. Böhler et al., Nanotechnology **15**, 465 (2004); M. Häfner et al., tbp

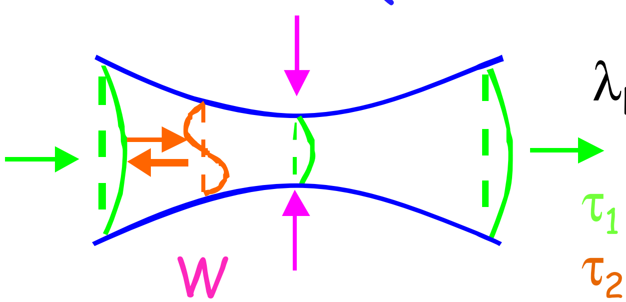
Calculation of transmission coefficients



Channels are eigenfunctions of scattering problem

Landauer formula: $G = \frac{2e^2}{h} D = G_0 D$ with $D = \sum_{n=1}^{N} \sum_{m=1}^{N} |t_{nm}|^2 = Tr(t^+ t) = \sum_{i=1}^{N} \tau_i$

Adiabatic QPCs



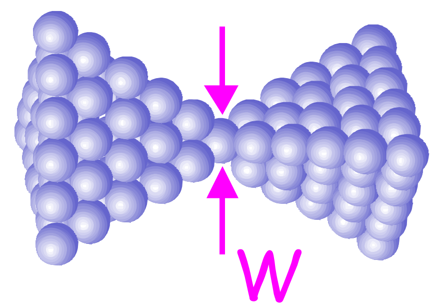
$\lambda_F \sim W \gg a$

$\tau_1 = 1$,

$\tau_2 = ... = \tau_N = 0$

Wavefunctions in reservoirs, leads and QPC are of same kind, well matched: $\tau_i = 1$ for all modes with $n\lambda_F/2 < W$

Atomic QPCs in metals:

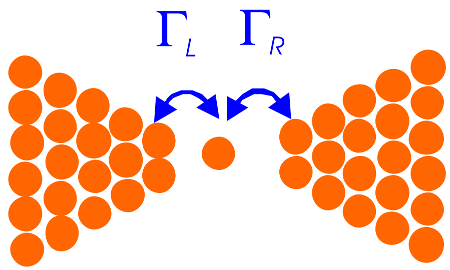


$\lambda_F \sim W \sim a$

$\tau_i = ?$

Wavefunctions in reservoirs and QPC are different: $\tau_i < 1$

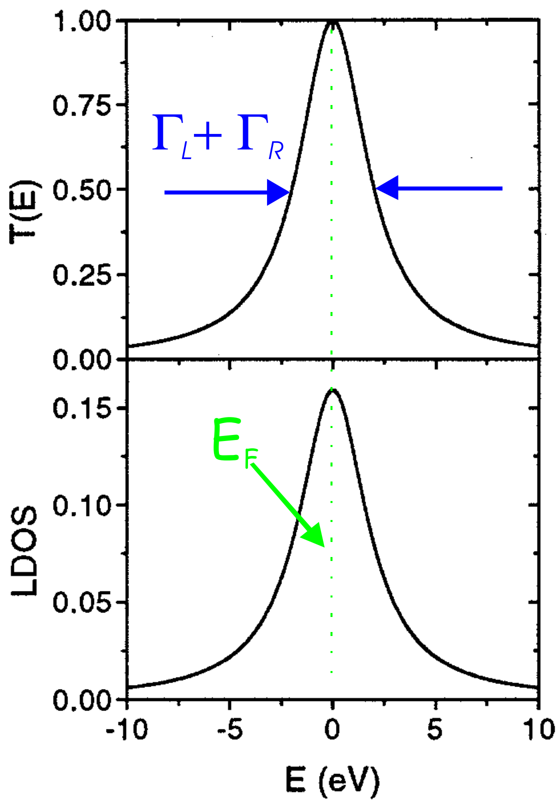
Localized orbitals model for monovalent metals



Breit-Wigner resonance

$$\tau(E) = \frac{4\Gamma_L \Gamma_R}{(E-\varepsilon)^2 + (\Gamma_L + \Gamma_R)^2}$$

with ε: effective level of central orbital



Parameters here:

$\Gamma_L = \Gamma_R = 1$ eV,

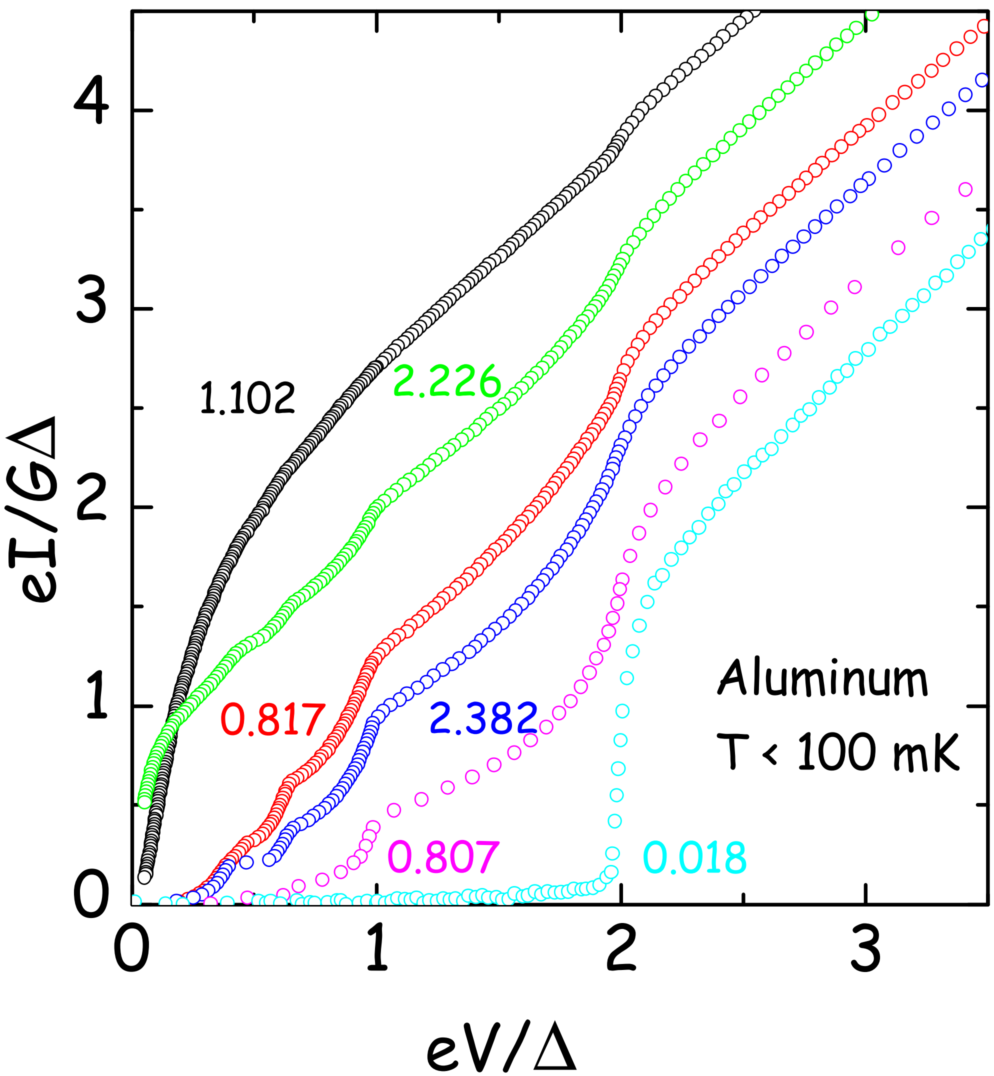
$\varepsilon = E_F = 0$ eV

$\tau = 1$ only if

- resonance centered at E_F (charge neutrality)
- $G_L = G_R$ (symmetric contact)

A. Levy Yeyati et al. PRB 56,10369 (97);
J.C. Cuevas, thesis, UA Madrid (99)

FROM TUNNELING TO CONTACT



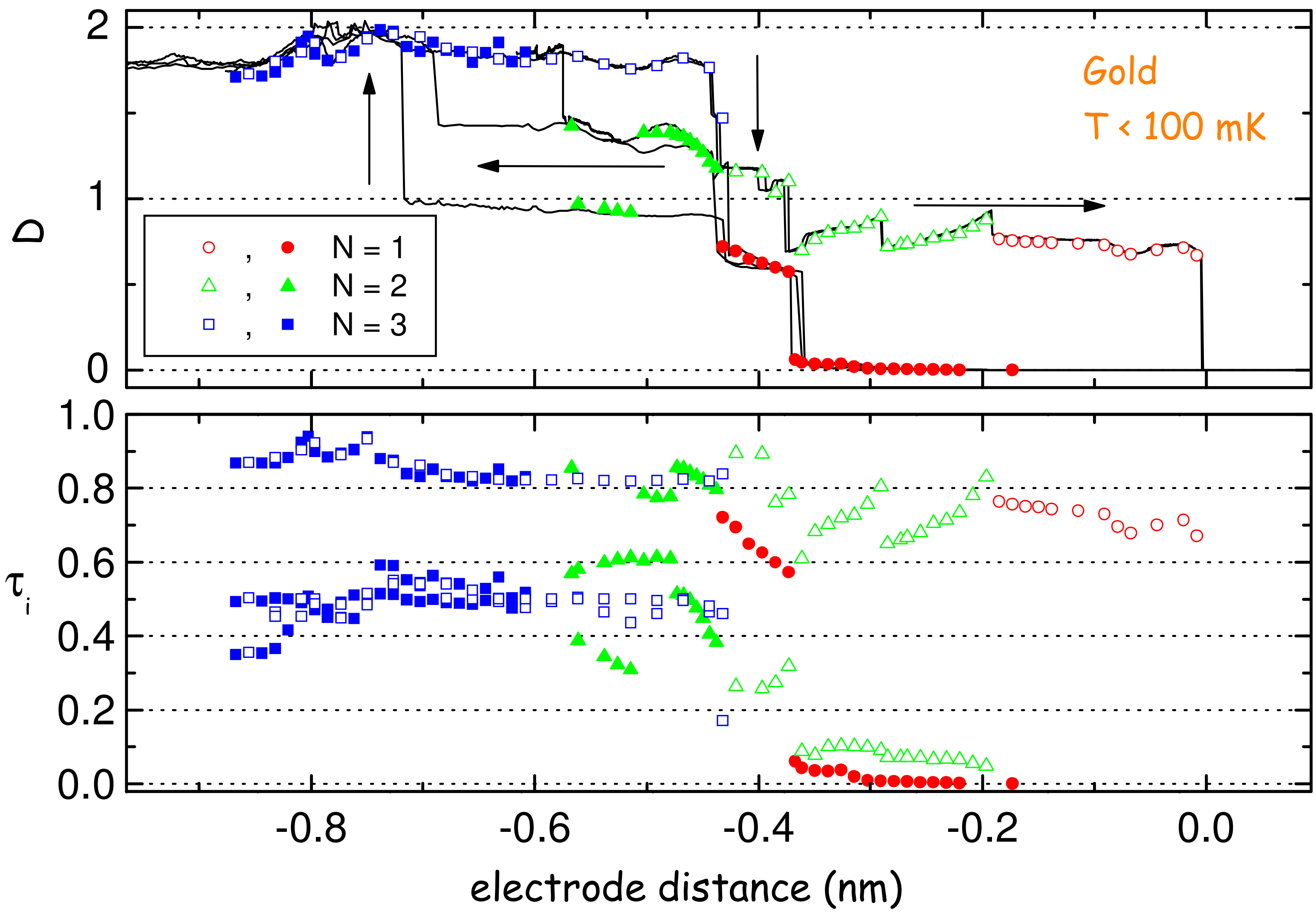
Δ : superconducting gap energy

G : conductance at eV » 2Δ

Nonlinear IV characteristics of superconducting atomic contacts:

- sub-gap structure
  (N. v. d. Post et al., '94)
- excess current
  (C. Muller et al., '92)
- supercurrent (not shown)
  (M. Goffman et al., '00)

Retracible opening and closing cycles

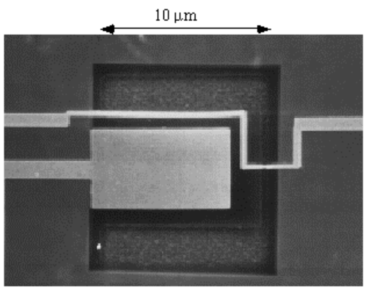


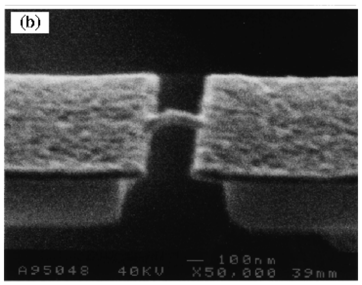
Possible Application of Single-Atom Contacts in Nanoelectronics

Vision:

Tailor-make electronic circuits with desired electronic properties by correct choice of atoms/clusters/molecules

Fully Integrated Break Junctions:

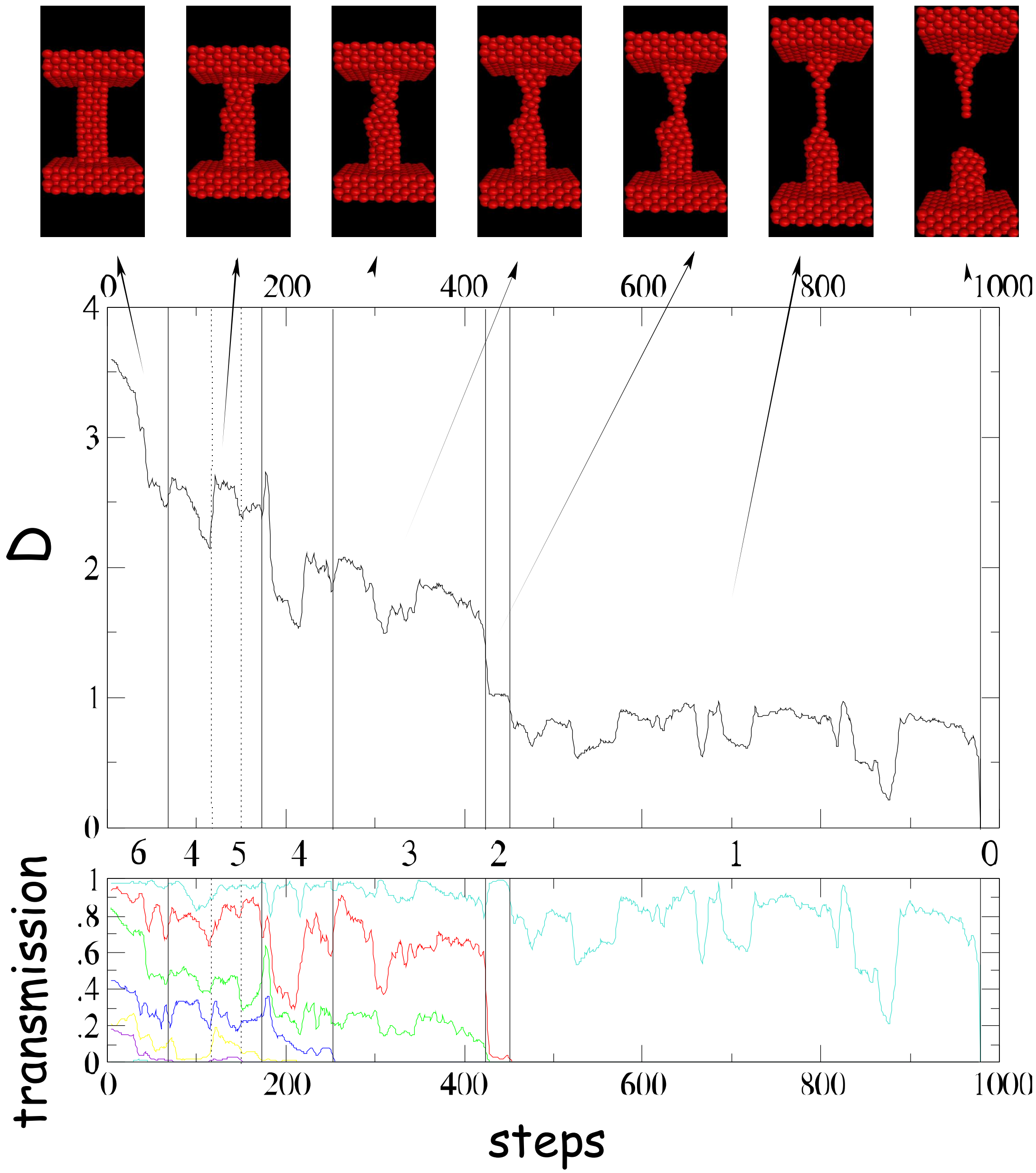




Open Problems:

1. Functionality: Find suitable building blocks for leads/switches/diodes!
2. Down scaling of MCB setup: (Zhou et al, 1995)
3. Control of atomic positions with subatomic precision?
4. Lifetime and reliability: Stability? Chemical reactivity?
5. Efficient, low-cost fabrication scheme: self assembly?
6. ....
7. ...

Formation of longer chains

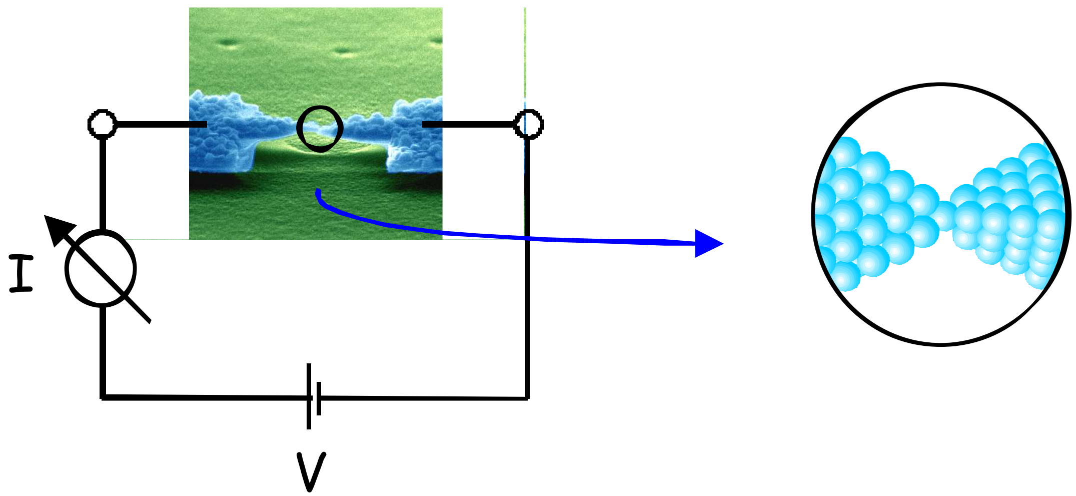


Combination of MD with tight-binding calculations:
$N_{atoms} = 112$
$T = 4.2$ K, $\Delta t = 1.2$ ps
8 atoms in cross section at the beginning

M. Dreher, P. Nielaba, J. Heurich, M. Häfner, J.C. Cuevas, to be published

Exp. Observation of chain formation:
Ohnishi et al. Nature 1998
Yanson et al., Nature 1998

Electronic Transport through Single-Atom Contacts of Ferromagnetic Metals



People:
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C. Bacca
V. Kunej
H.-F. Pernau

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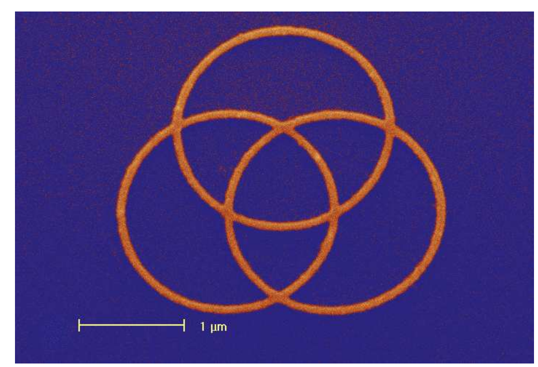
H.v. Löhneysen (Karlsruhe), W. Belzig (Basel),
J.M. van Ruitenbeek (Leiden), N. Agrait (Madrid)

Financial support: DFG and Krupp Foundation



METALLIC QUANTUM POINT CONTACTS (QPC)

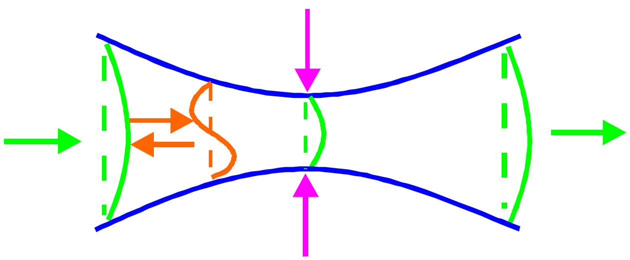
Low electron density metals

$\lambda_F \gg a_0$

$W \sim \lambda_F$

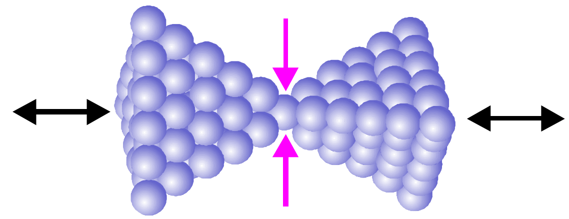
High electron density metals

$\lambda_F \sim a_0$

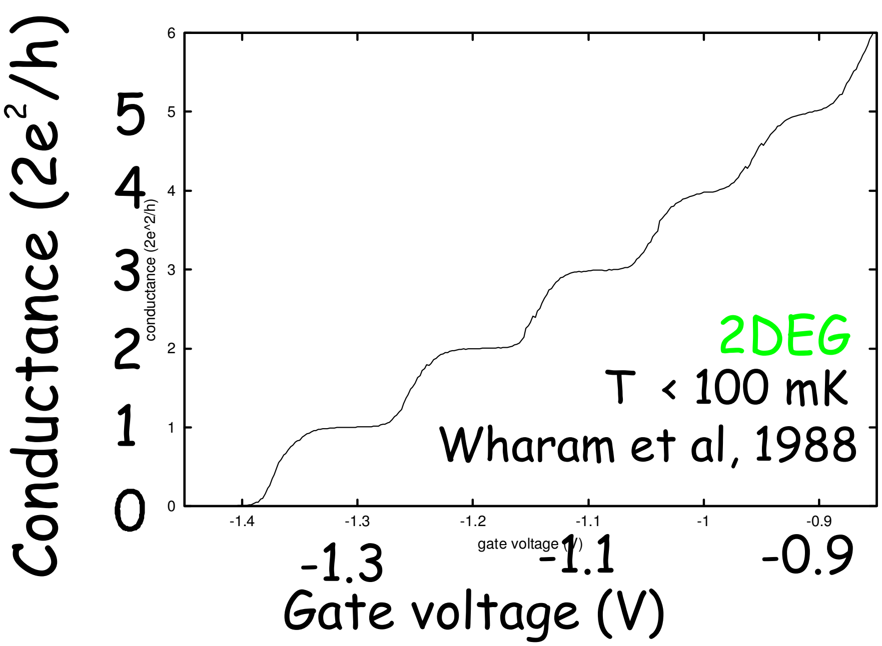


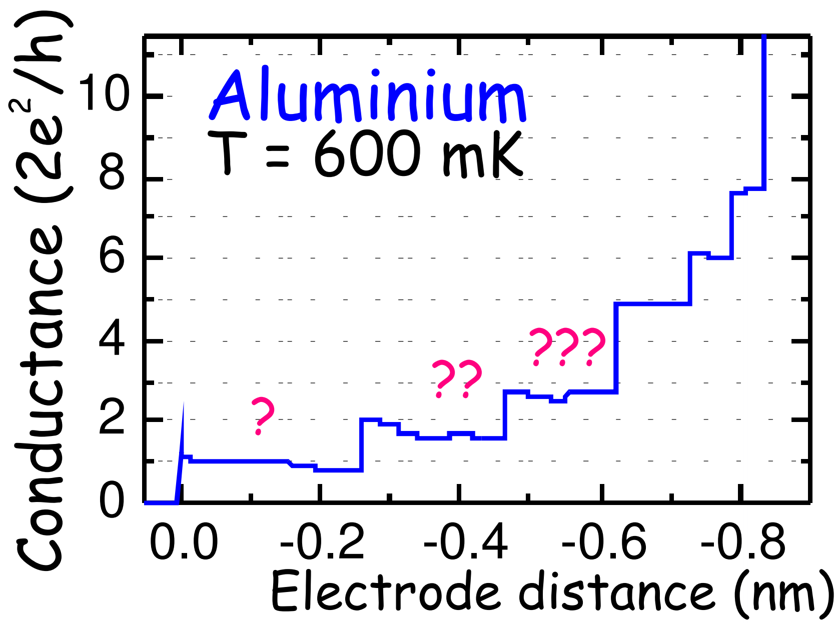
$\tau_1 = 1,\ \tau_2 = \ldots = \tau_N = 0$

$$G = \frac{2e^2}{h} \sum_{i=1}^{N} \tau_i$$



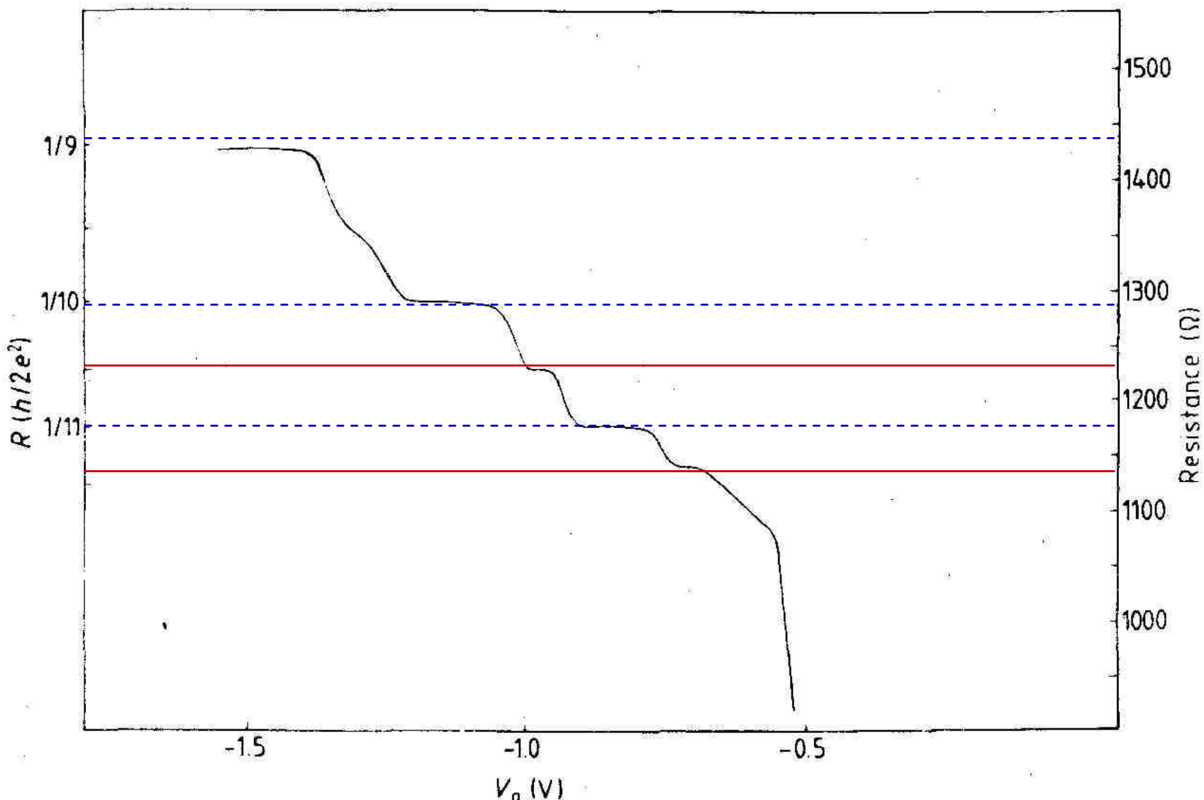
$\tau_i = ?$





Adiabatic QPC in strong magnetic field

Lifting the spin degeneracy: $$G = \frac{e^2}{h}\sum_{n=1}^{N}(\tau_{n\uparrow} + \tau_{n\downarrow})$$



Appearance of new plateaus at

$$G = \frac{e^2}{h}(2i+1)$$

Wharam et al., J. Phys C (1988)

Theory:
Imamura et al., PRL 2000