Electron transport in magnetic quantum point contacts

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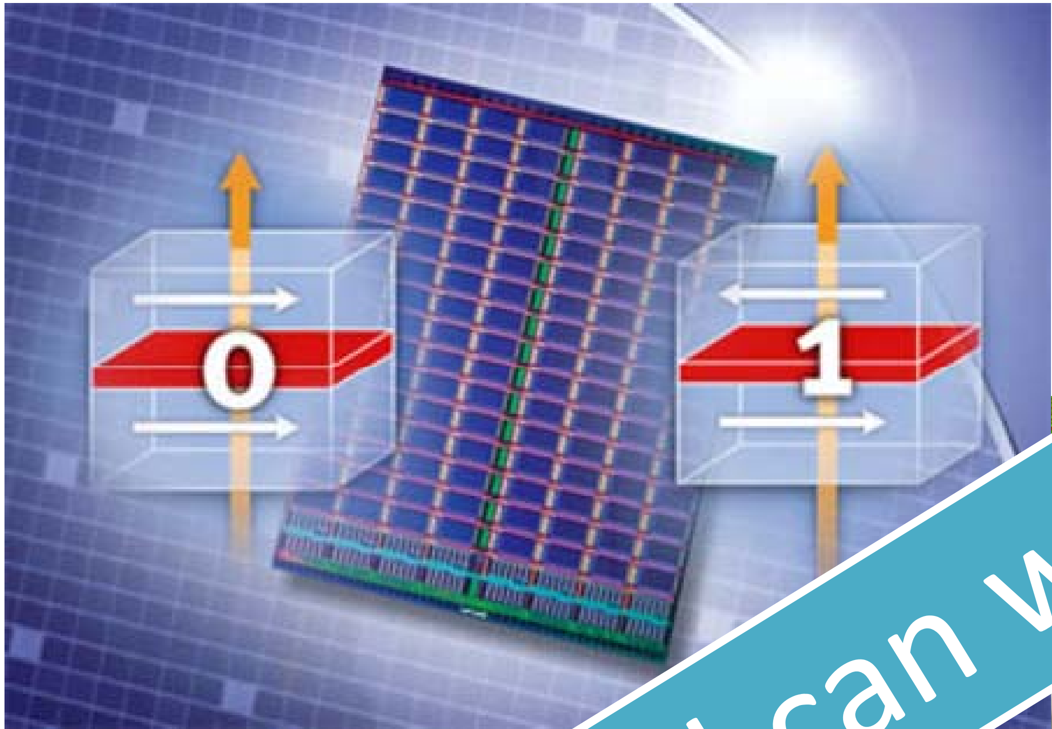
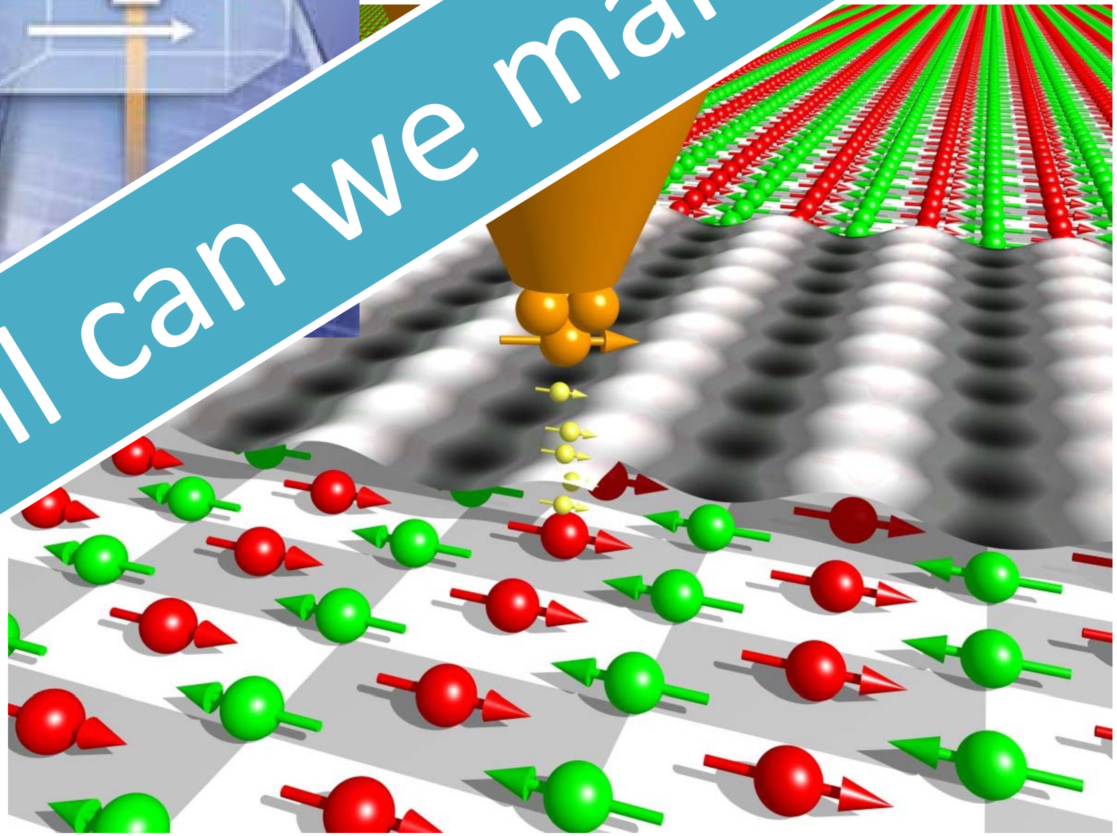
XLVI Zakopane School of Physics May 21st 2011

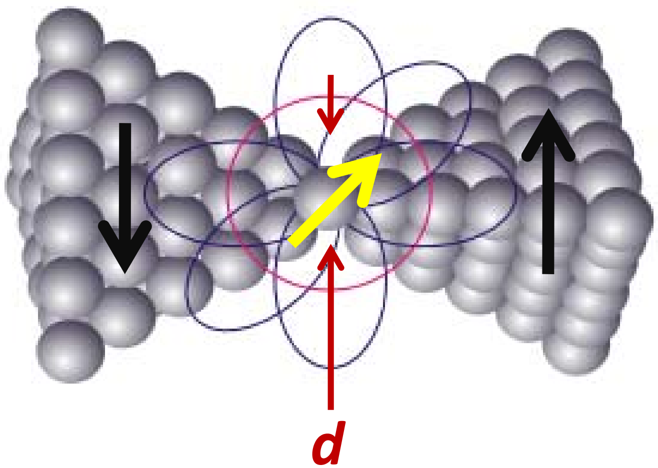




How small can we make it?

classical bulk wire

$$G = \frac{I}{U} = \frac{1}{\rho}\frac{\pi d^2}{4l}$$



Single Atom Magnetic ***Quantum Point Contact***

$$d \approx \lambda_F \longrightarrow$$ full quantum regime

- relatively simple model system
- comparision of theory and experiment
- access to fundamental electronic and mechanical properites of matter at the atomic scale

Outline

- Experimental realisation of magnetic QPCs
- Quantised conductance in single-atom contacts
- Magnetoresistance of ferromagnetic Co QPS
- Potetial magnetism in single-atom Pt contacts
- Heterocontacts between magnetic and normal metals

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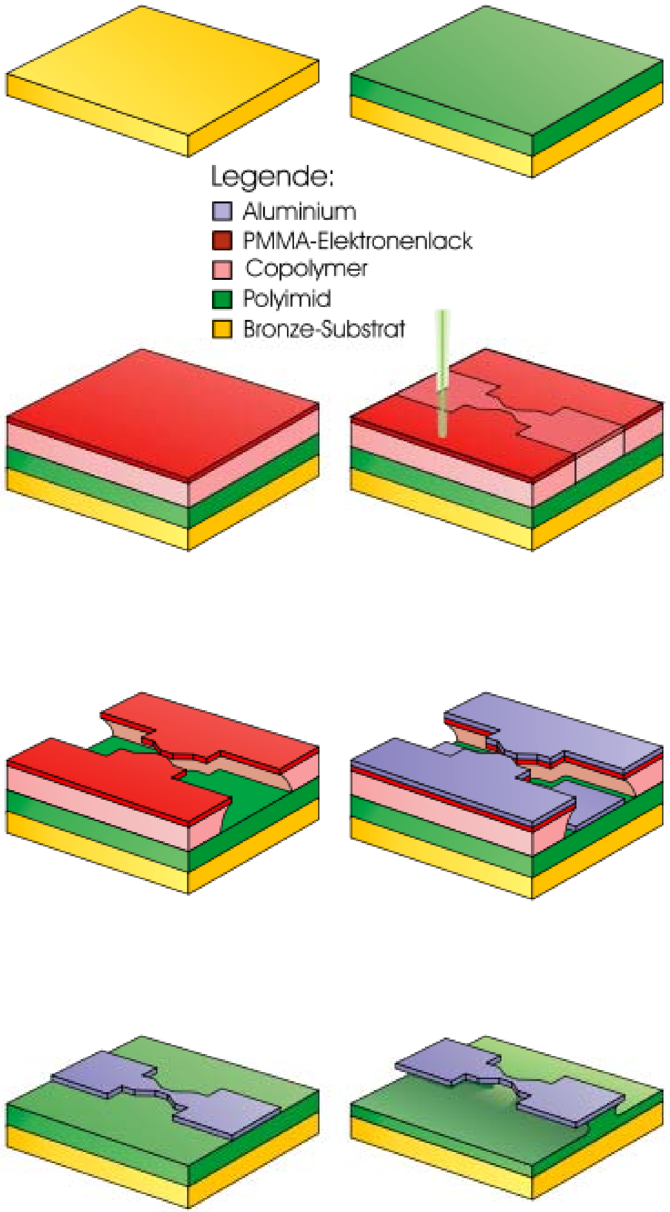
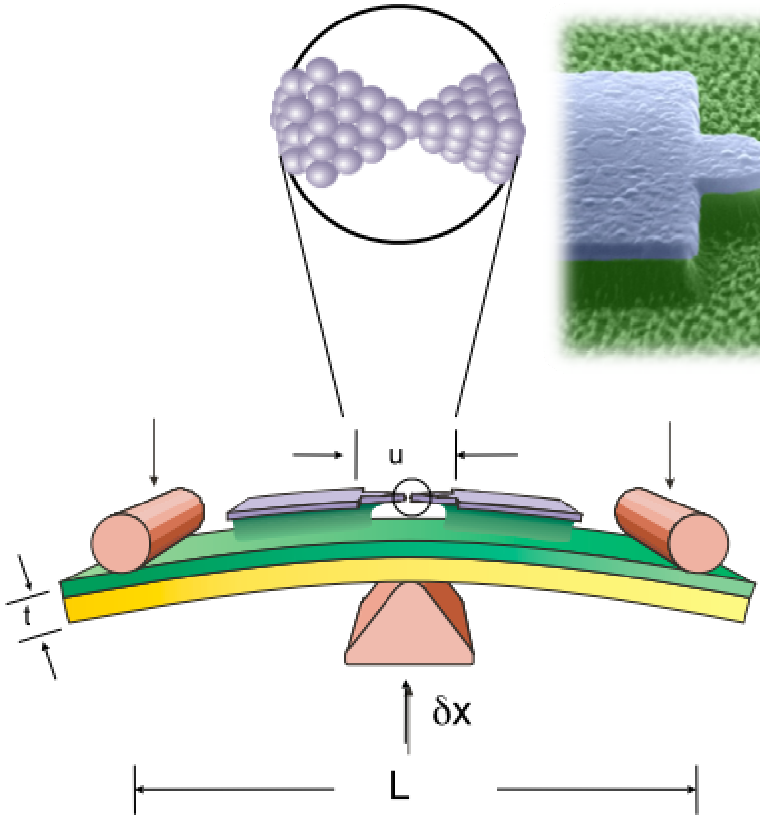
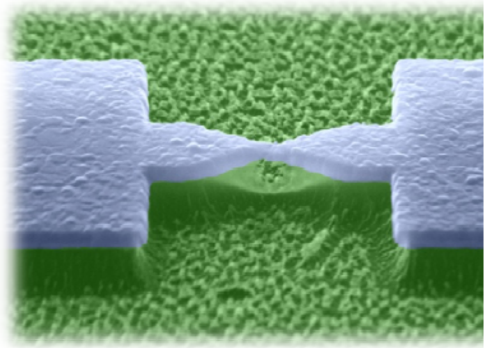
Microfabricated MCBJs





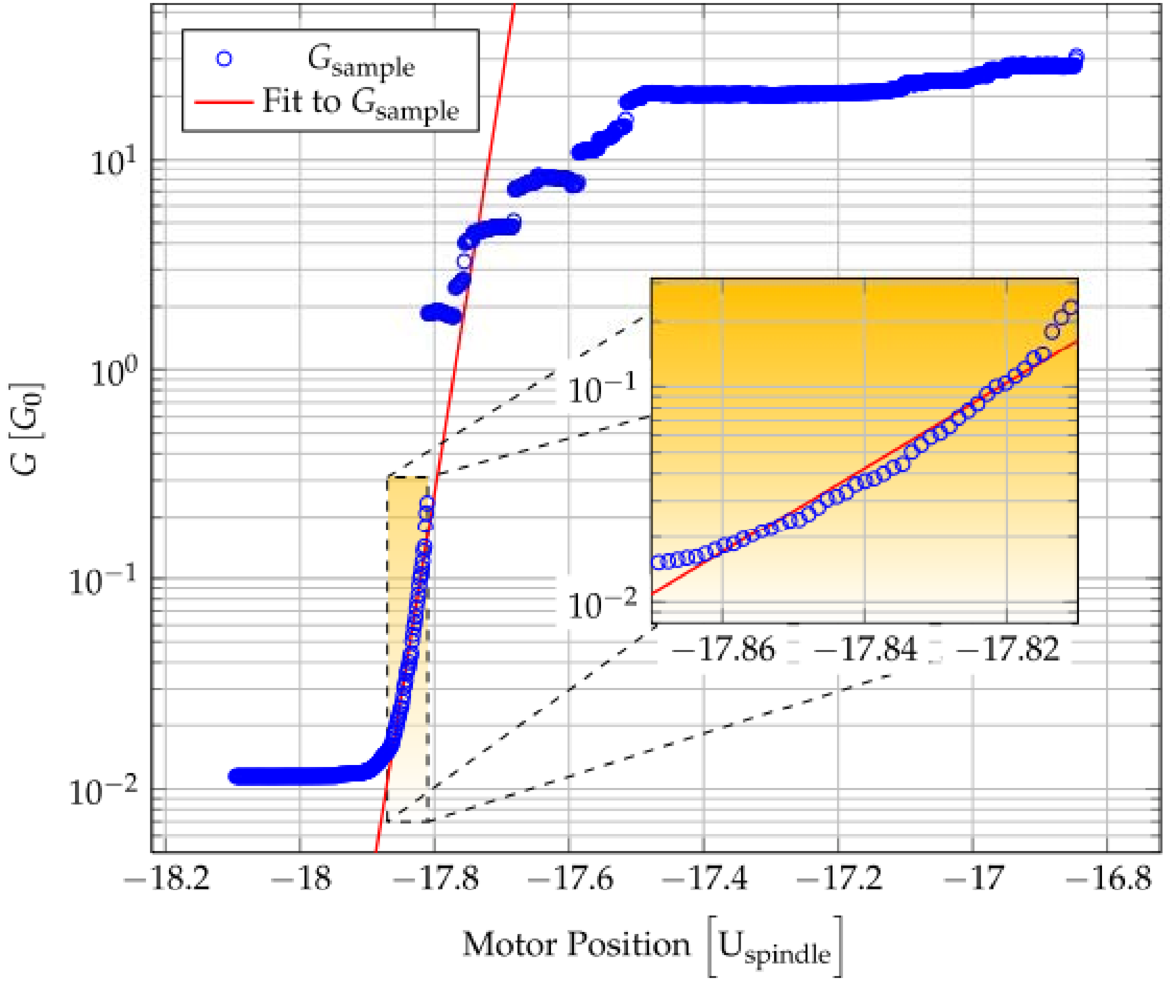


$$\delta u = r \cdot \delta x$$

$$r = \frac{6t \cdot u}{L^2} \approx 10^{-4} \ \dots . \ 10^{-5}$$

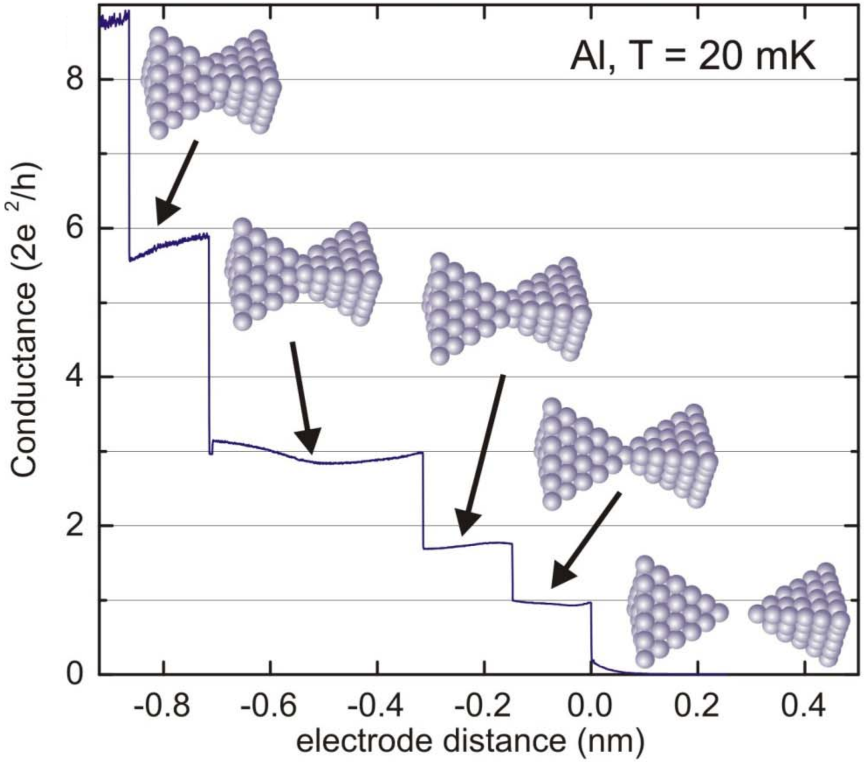
$\delta x = 1\mu m \longrightarrow \delta u \approx 0.01 nm = 0.1 Å$

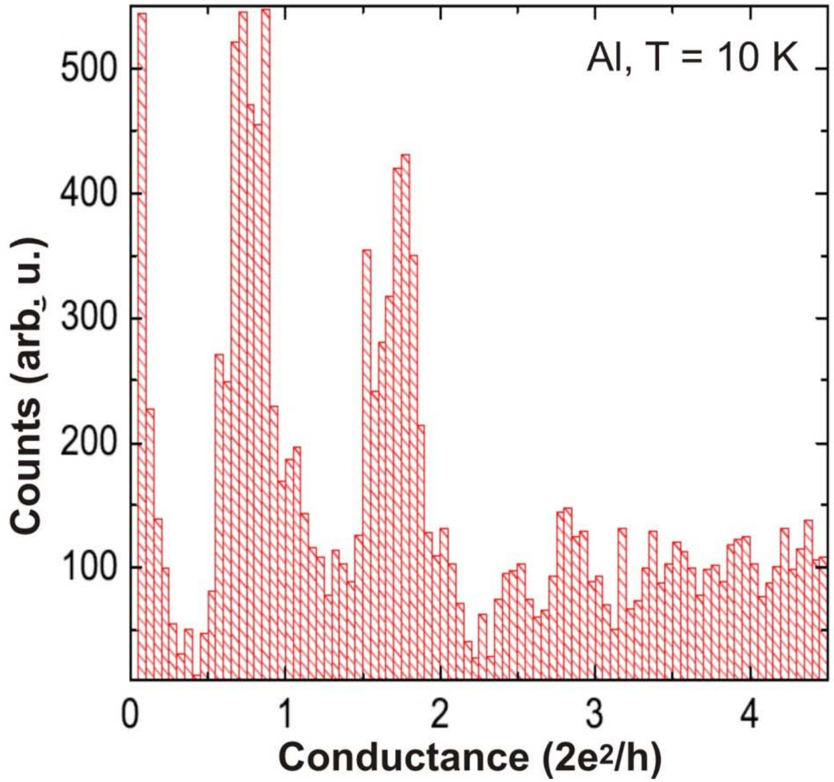
MCBJ distance calibration



$$I \propto U \cdot \exp\left(-\frac{2}{\hbar} \sqrt{2m\Phi} \cdot D \right)$$

opening traces and conductance histograms





- step-like conductance changes of $\Delta G \approx n\ 2e^2/h$
- sudden atomic rearrangements in the contact
- current densities up to 10^{12} A/cm

- statistical analysis of opening traces
- prefered conductance value of single-atom contact
- material specific fingerprint

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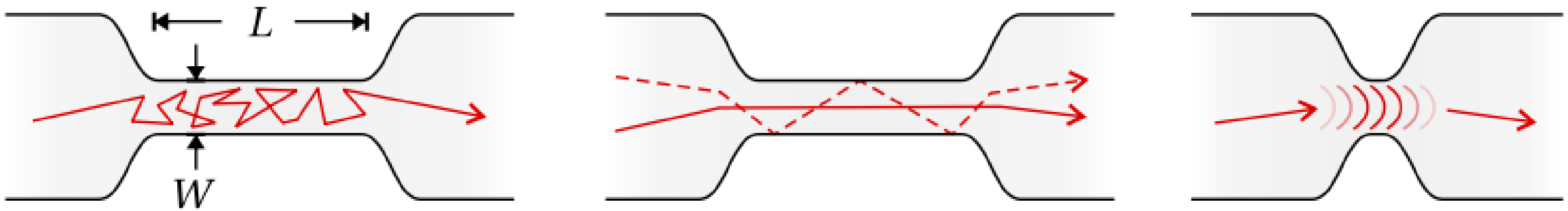
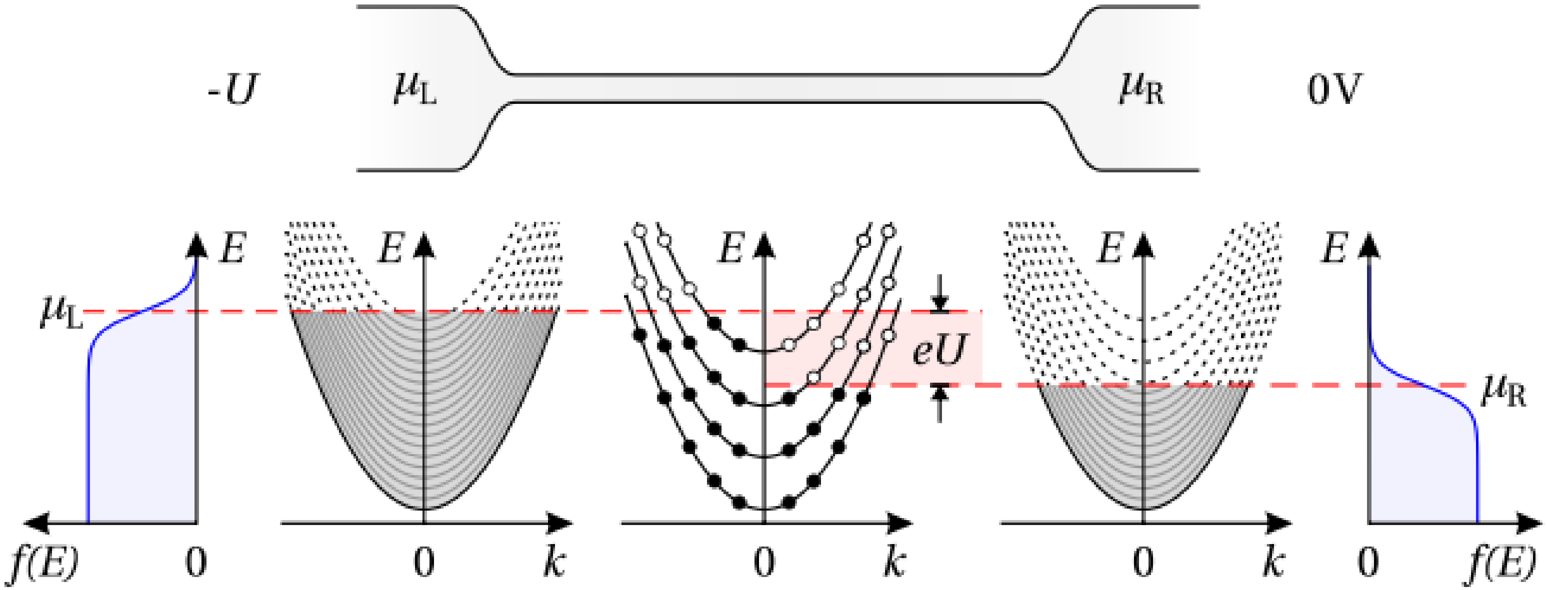
transport in mesoscopic conductors



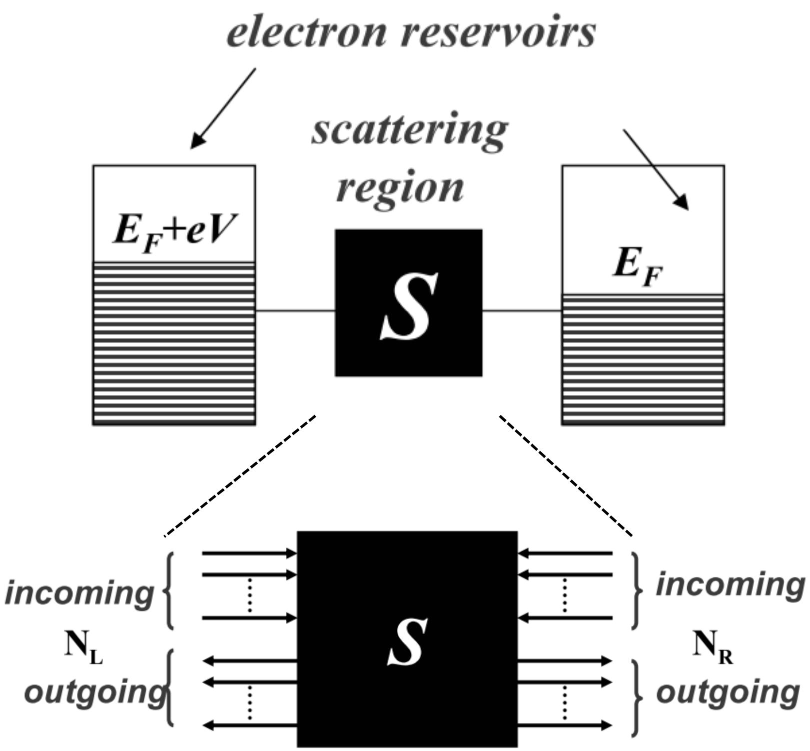
diffusive | ballistic | quantum regime

$l_\varphi > L, W >> l_e$ | $L, W < l_e \approx 100nm$ | $L, W < \lambda_F \approx 5\,\mathring{A}$



C. Schirm, PhD Thesis, University of Konstanz (2010)

the concept of conductance channels



$$S = \begin{pmatrix} r & t' \\ t & r' \end{pmatrix}$$

scattering matrix S is a N_Lx N_R matrix

Landauer Formula

each atom supports *N* conduction channels with arbitrary transmittance τ_n

spin degeneracy

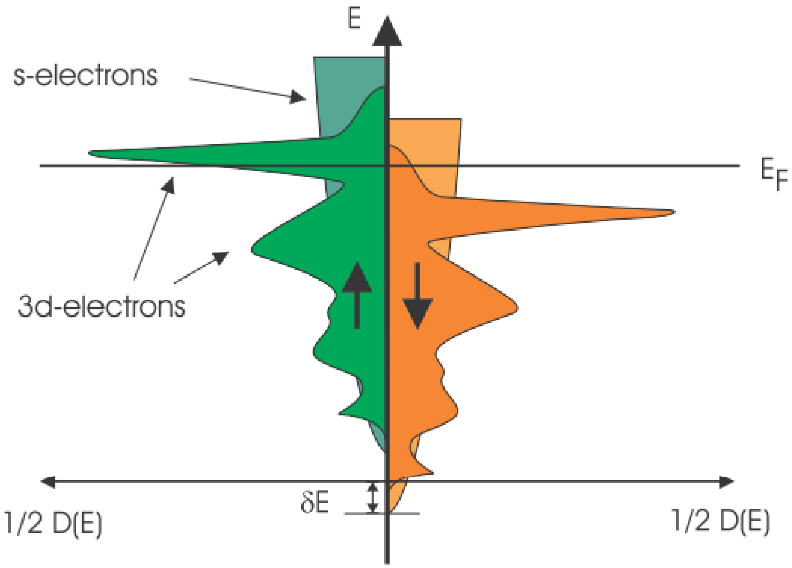
$$G = \frac{I}{V} = \frac{\mathbf{2}e^2}{h}\sum_{n=1}^{N}\tau_n$$

N - depends on valence orbital structure

one channel N=1 with perfect transmission *τ=1*: conductance quantum:

$$G = \frac{2e^2}{h} \equiv G_0 \approx \frac{1}{12906}\Omega^{-1}$$

N. Agraït et al. / Physics Reports 377 (2003) 81–279



<u>in ferromagnets</u>

exchange splitting leads to spin-polarization at the fermi edge and lifts spin-degeneracy

spin-resolved Landauer equation:

$$G = \frac{e^2}{h} \sum_{n=1}^{N} \left(\tau_{n,\uparrow} + \tau_{n,\downarrow} \right)$$

in case of N fully spin-polarized channels e.g. $\tau_{\uparrow}$ =0 and $\tau_{\downarrow}$= 1:

$$G = \frac{e^2}{h} N$$

special situation leads to half-integer steps of the condtance quantum (G_0)
BUT usually all modes are partially open

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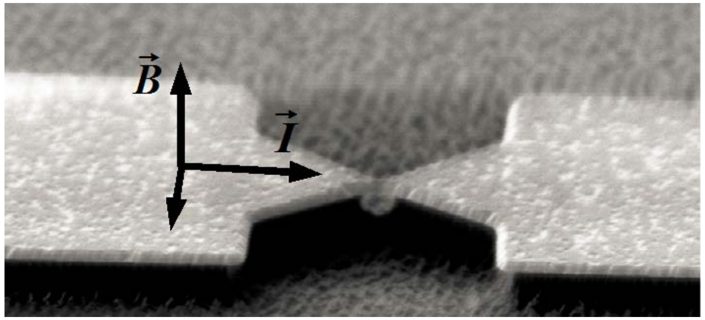
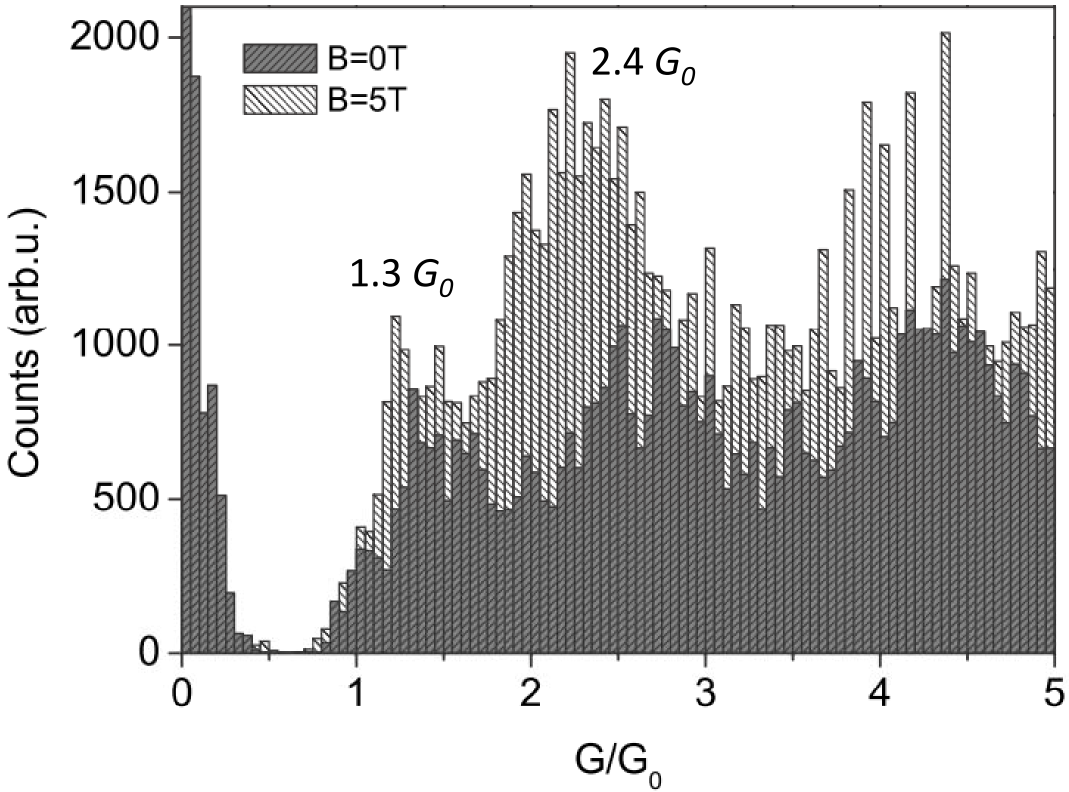
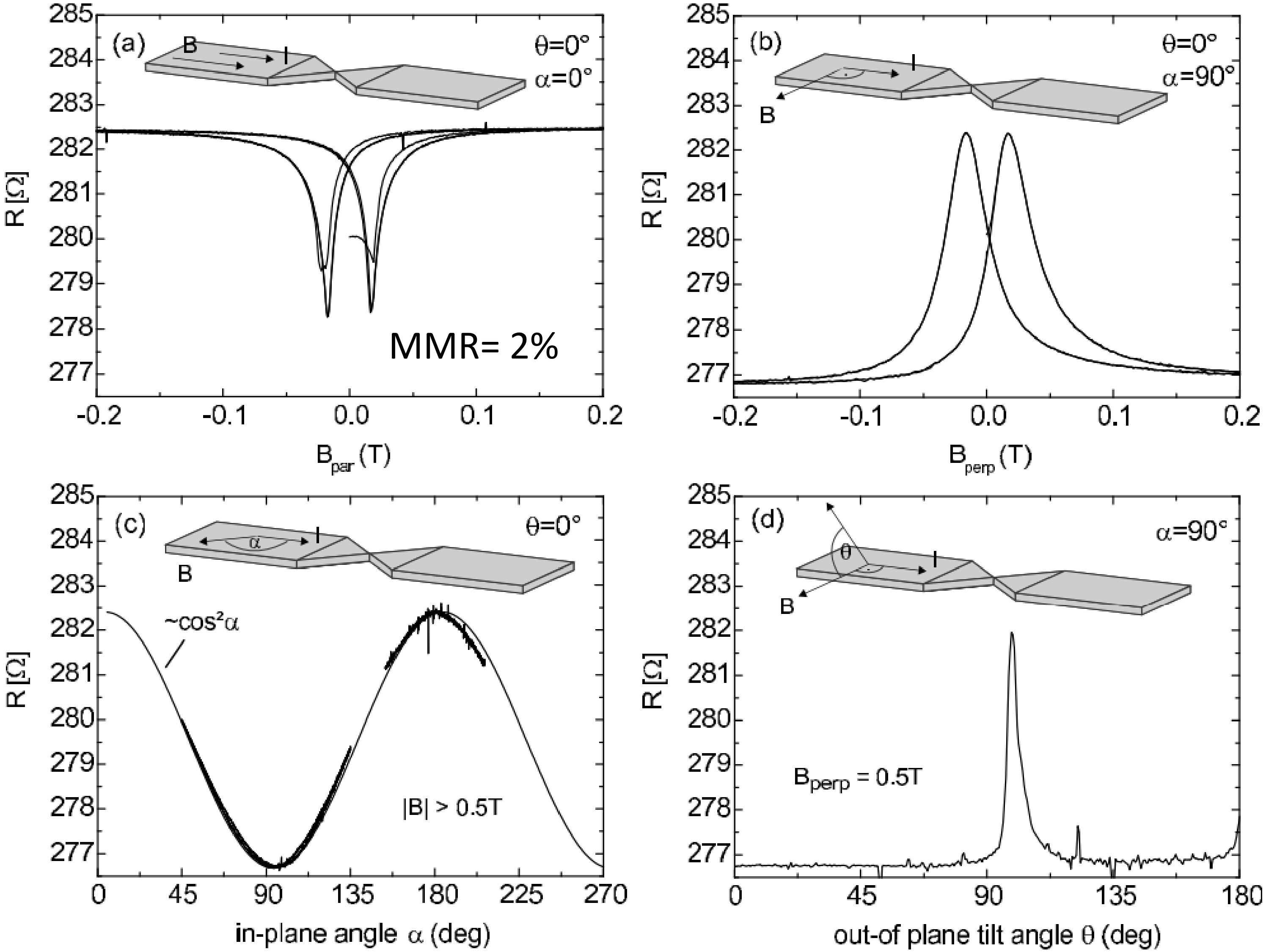
ferromagnetic Co MCBJs



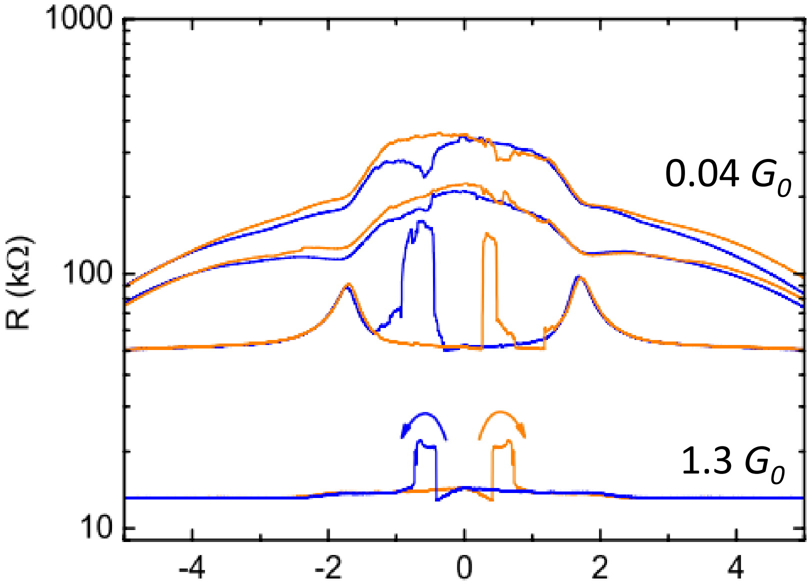


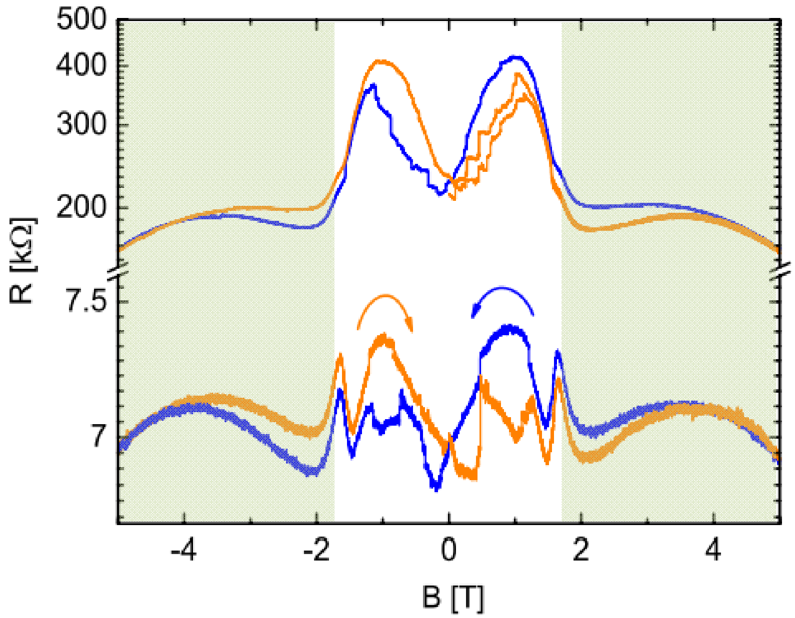
- no $G_0/2$ peaks observed in the histogram
- prefered conducance unchanged 1.3 G_0 and 2.4 G_0 independent of B
  → no BMR effect, e.g. B-dependent closing of conductance channels

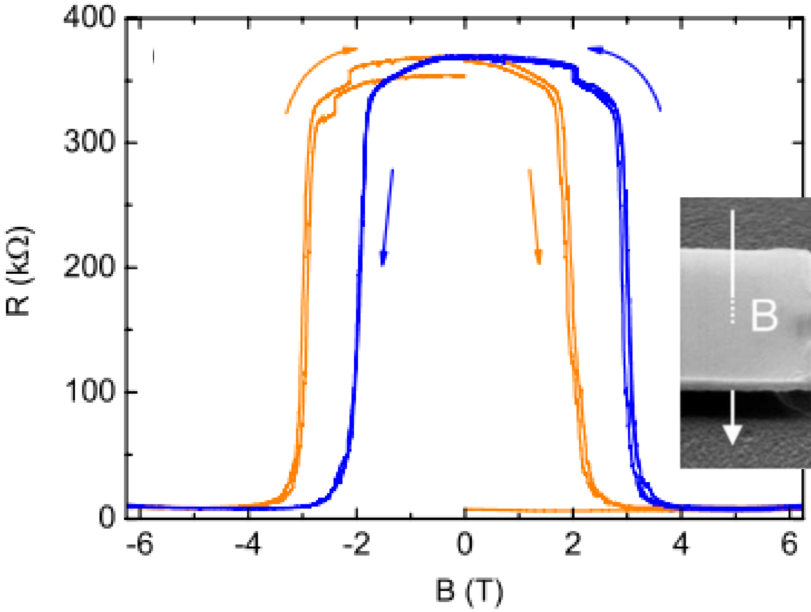
MR of unbroken Co MCBJs

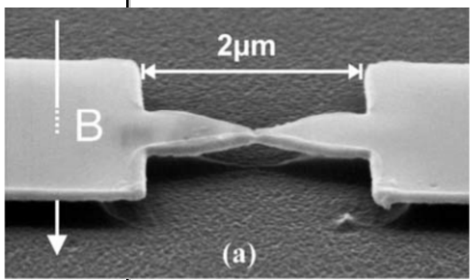


MR in ferromagnetic Co MCBJs





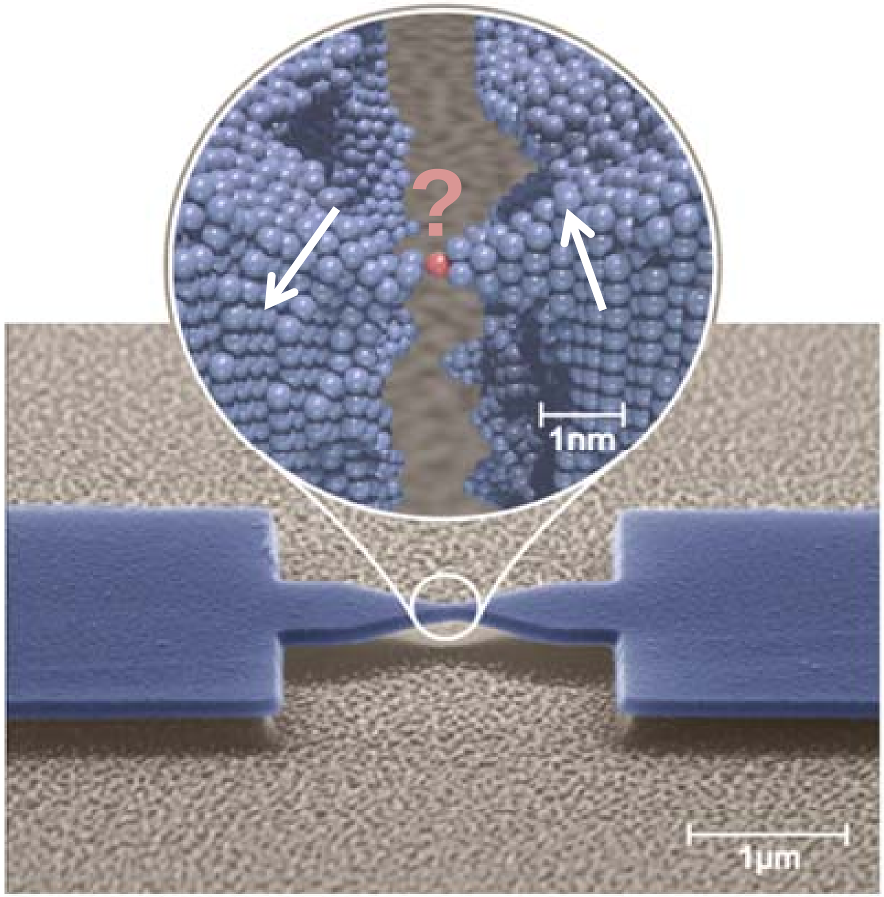




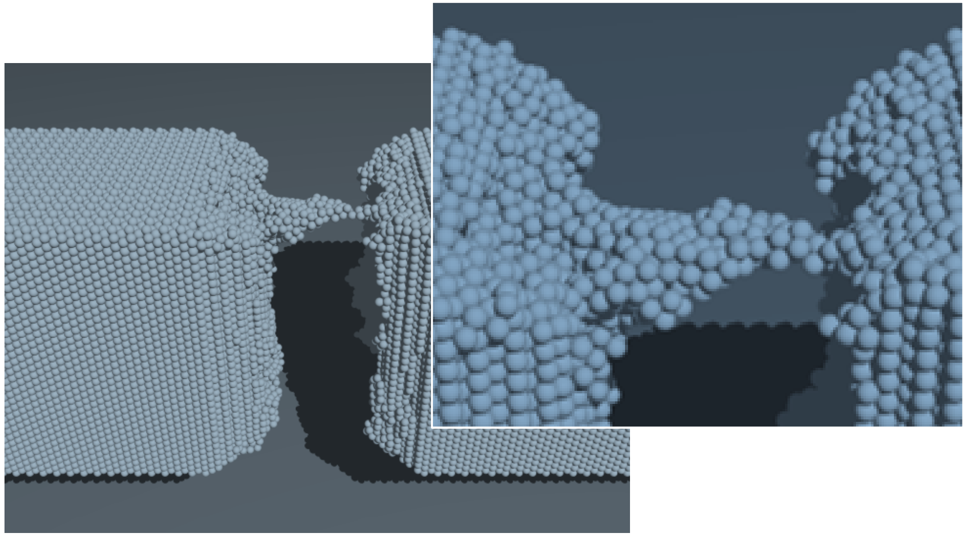
diverse MR behaviour

- step-like features for B< 2T
- continious change for B> 2T

origin of MR effects I



spin-dependent scattering in the electrodes (GMR, TMR)



B modifies energy landscape in the constriction

equilibrium configuration becomes instable + magnetostriction

field-induced reconfiguration of the contact at the atomic scale

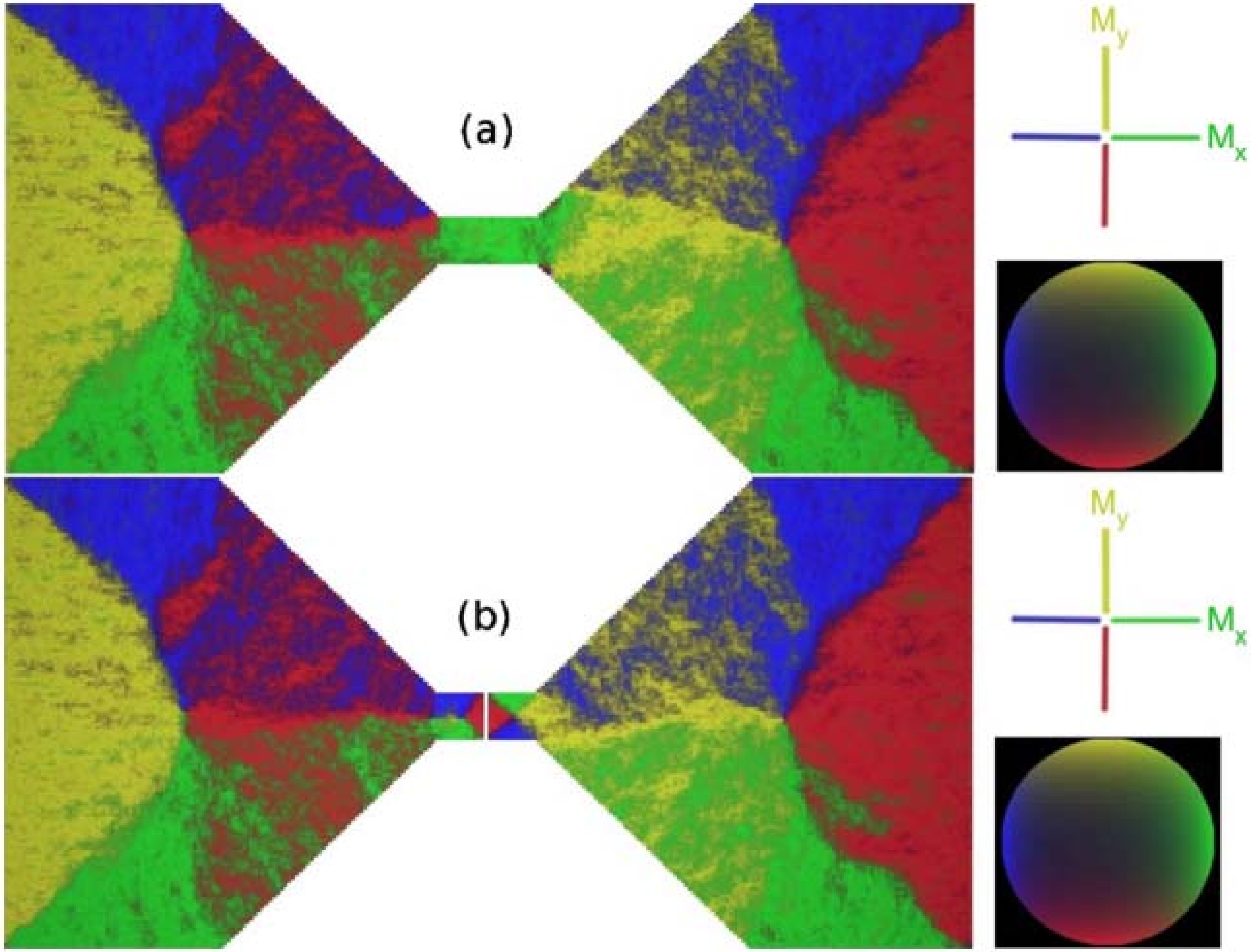
Shi et al., Phys. Rev. B, 76 (2007)

Co MCBJ magnetic microstructure

Remanent state:

M_S= 1.43·10^6 A/m
K= 6.8 ·10^5 J/m^3

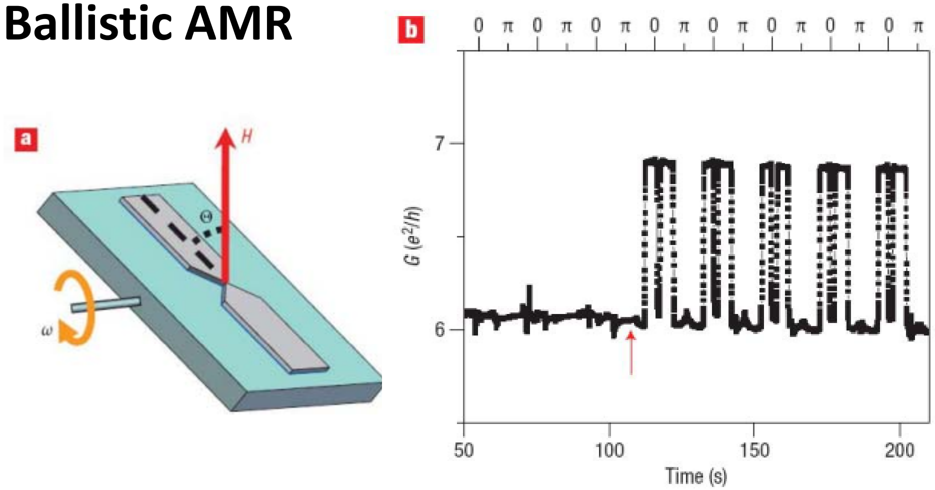
Saturation @ 2T



formation of domain-closure vortices states in fully broken MCBJs

origin of MR effects II

Ballistic AMR

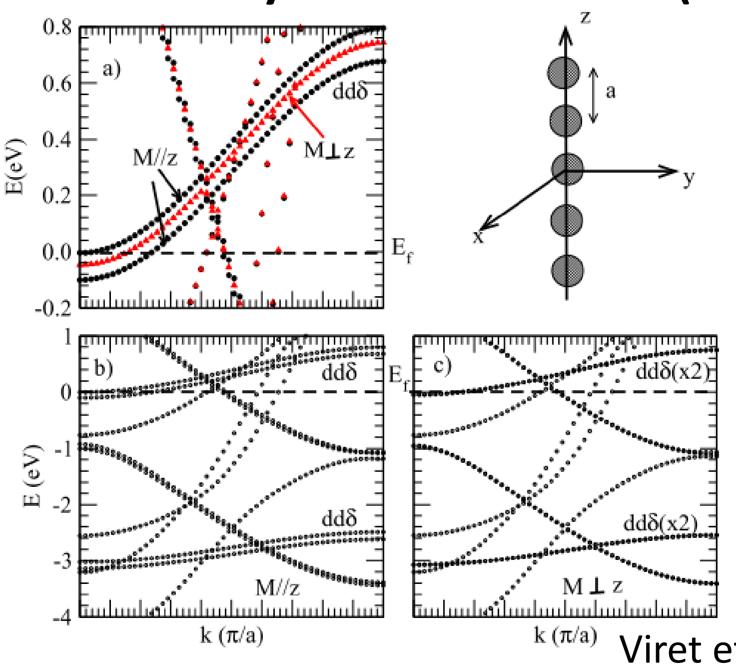


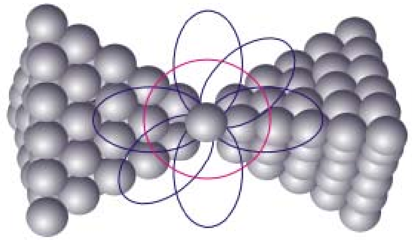
field dependent closing of perfect, spin-polarised channels

ΔG≈ n e²/h

Sokolov et al., Nat. Mat., (2007)

Atomically - enhanced AMR (AAMR)





- unquenching of electron orbital momentum in constricted region
- modified band structure
- higher saturation fields

Viret et al., arxiv Cond. Mat., (2006)

Single Atom Co Contacts

- ***diverse MR behavior, with MR up to 200% in contact regime***

- ***various contributions of ferromagnetic leads AND constricted region***

- deconvolution of these effects via additional experiments

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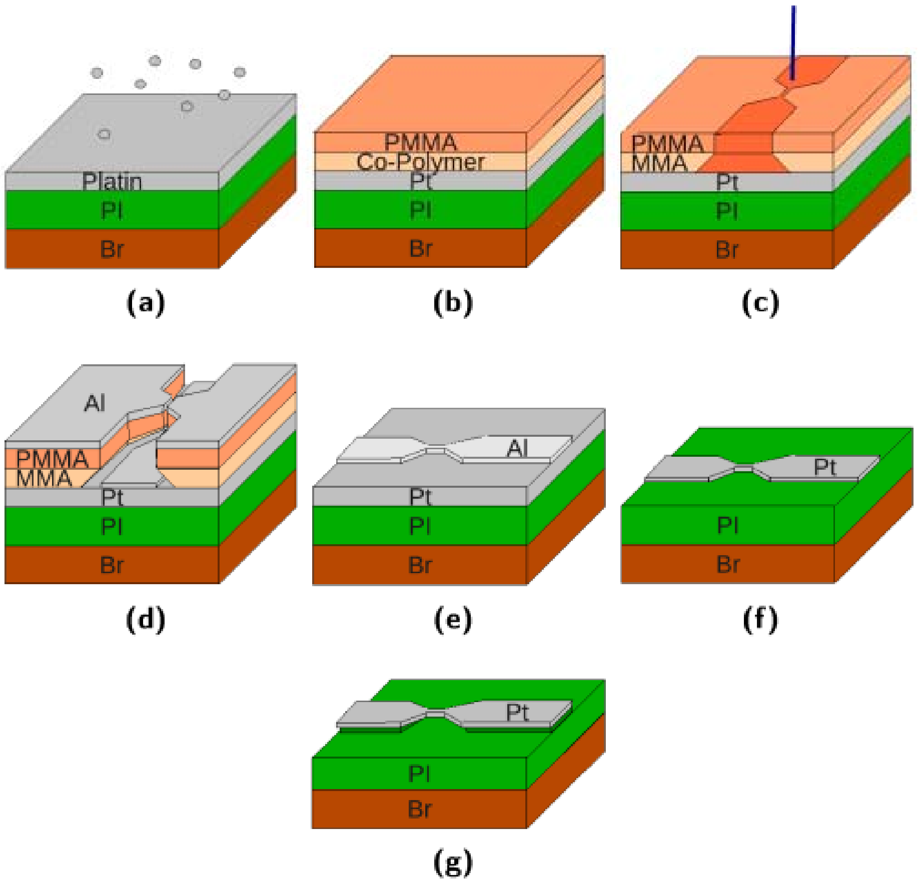
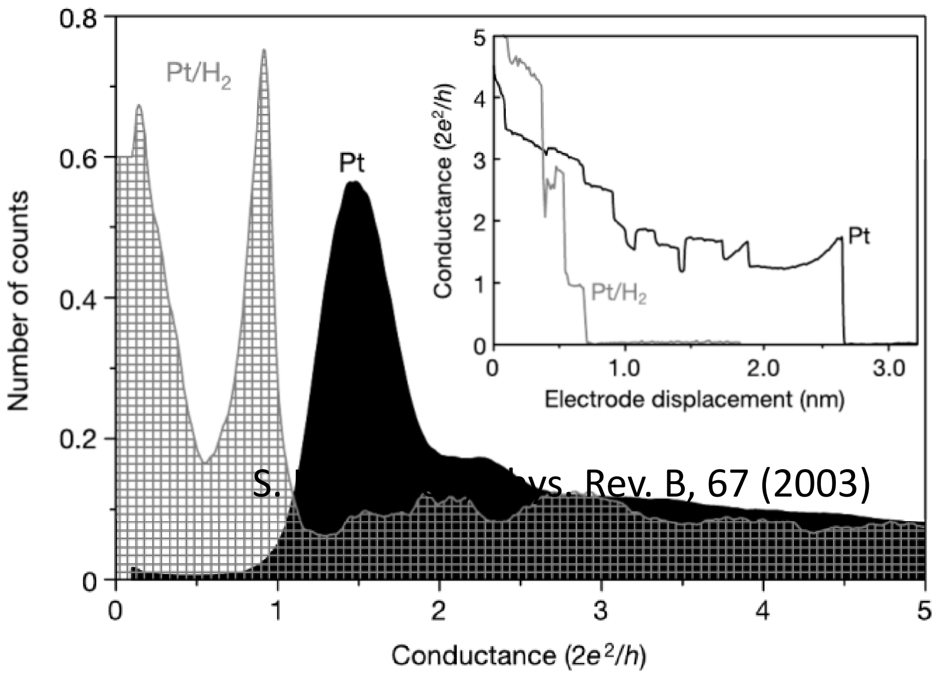
Fabrication of Pt MCBJs

Why Pt

Pt close to Stoner criterion, hence „nearly“ magnetic

strong spin-orbit coupling --> potetially high AAMR

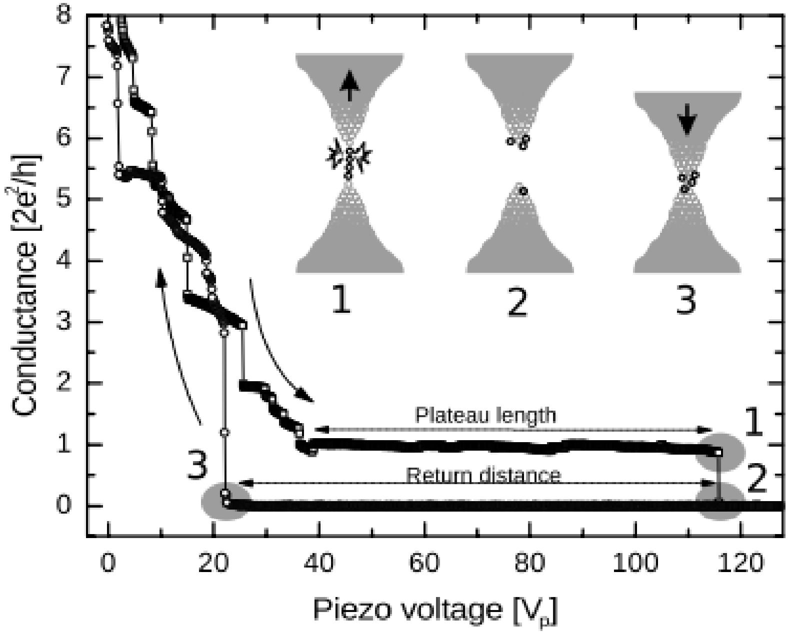


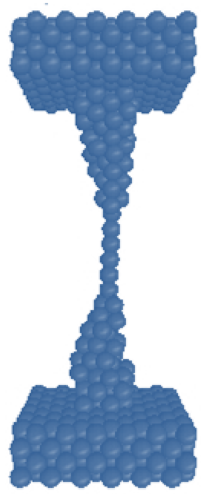


S. ... ys. Rev. B, 67 (2003)

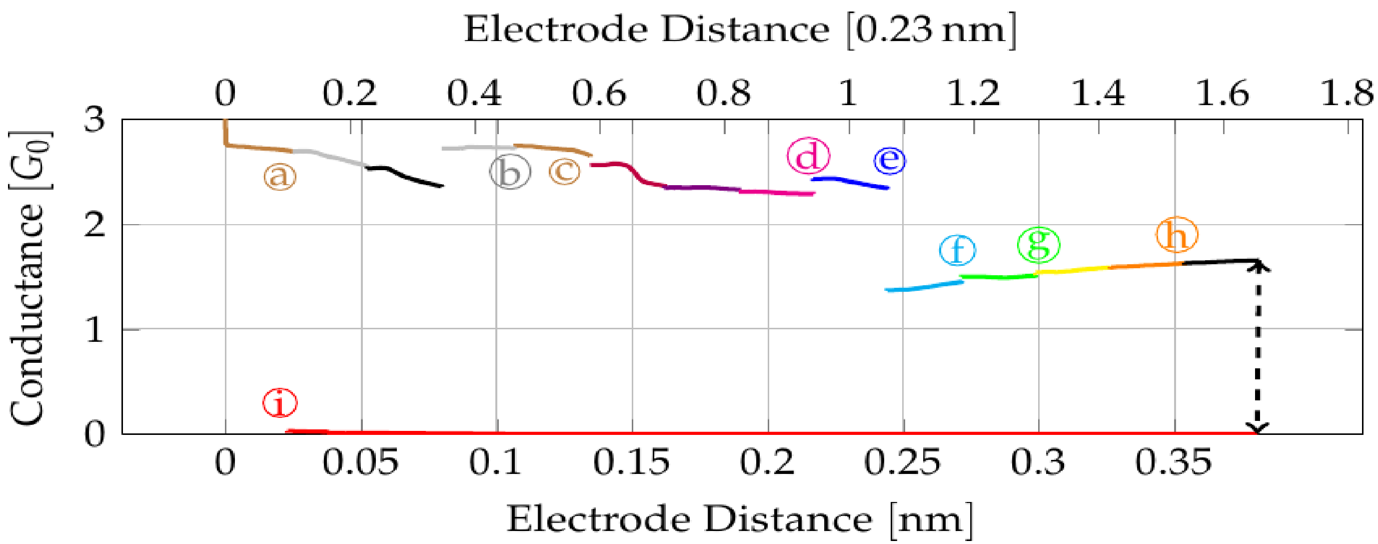
Pt chain formation

A. Yanson, PhD Thesis, Leiden (2001)

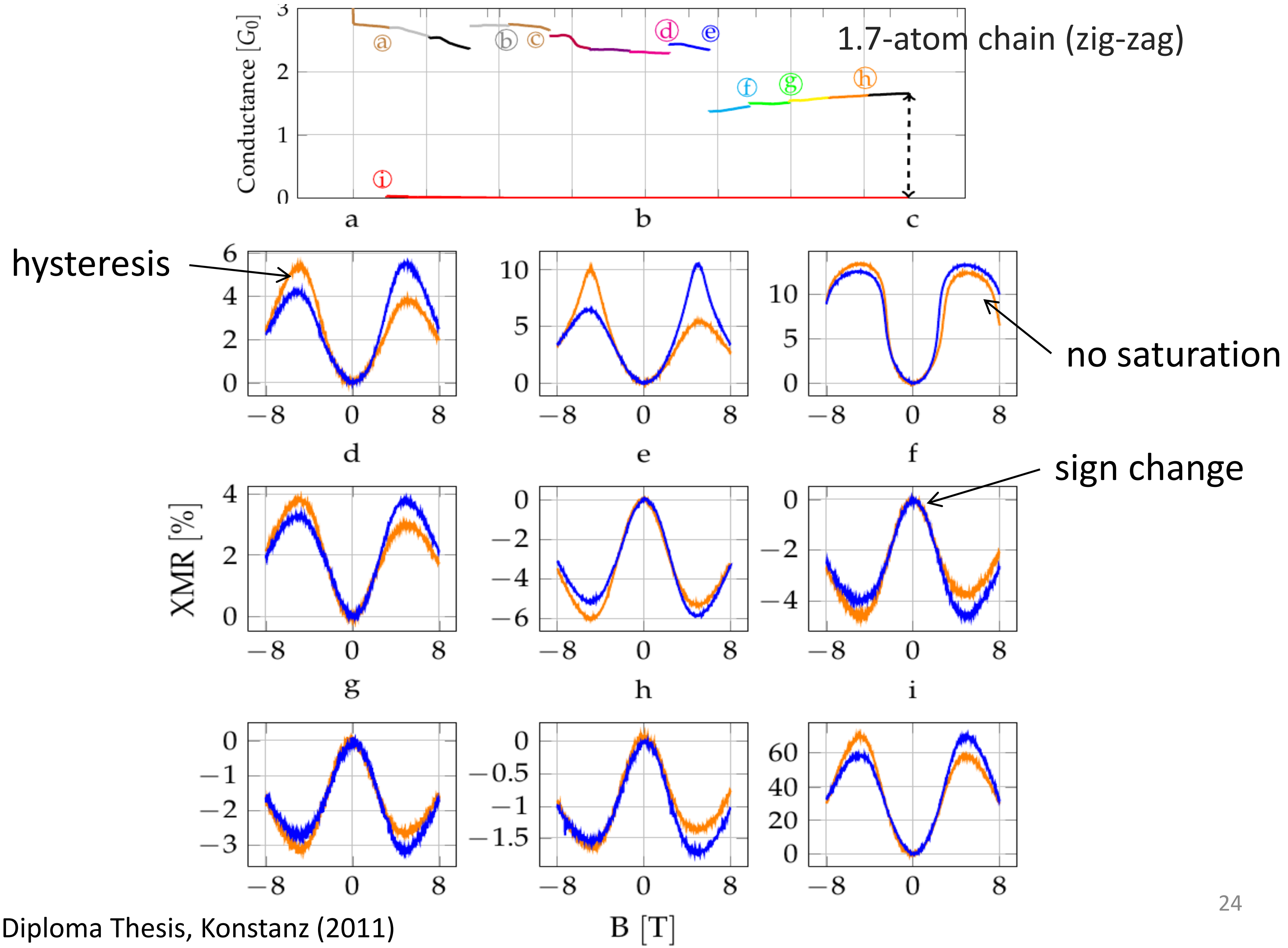




[courtesy J. Cuevas]

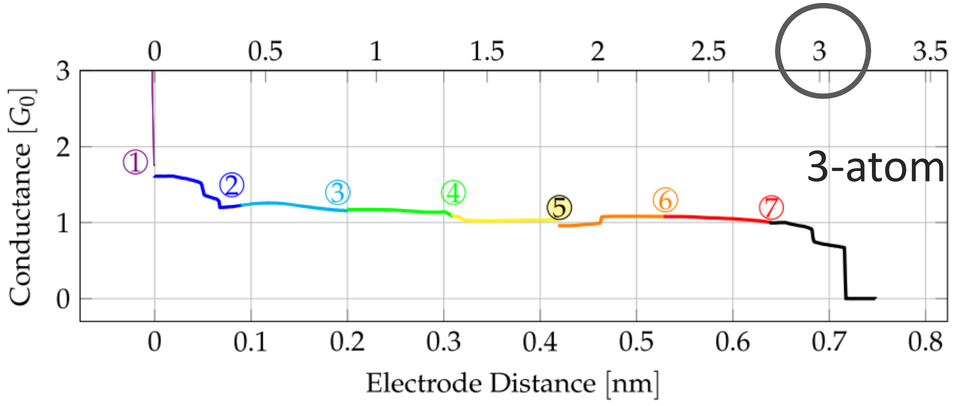


MR of Pt mono-atomic chains

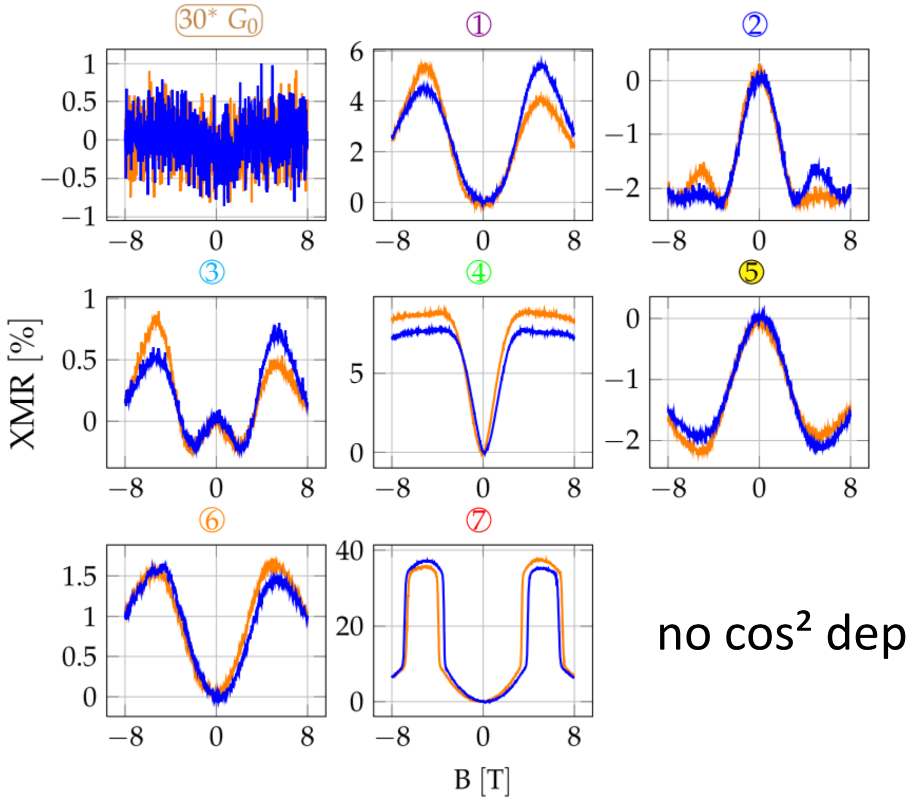


C. Espy, Diploma Thesis, Konstanz (2011)

MR of Pt mono-atomic chains



(a)



no cos² dependence

Mono-atomic Pt chains

- ***large XMR up to 20% in the atomic contact regime***

- non-trivial AAMR behaviour

- MR changes magnitude and sign depending on chain length

- hysteresis possibly due to magnetically ordered sub-unit in contact

- ***evidence for spontaneous magnetization of Pt at the atomic scale***

does this indicate a spin-polarization of transport channels ?

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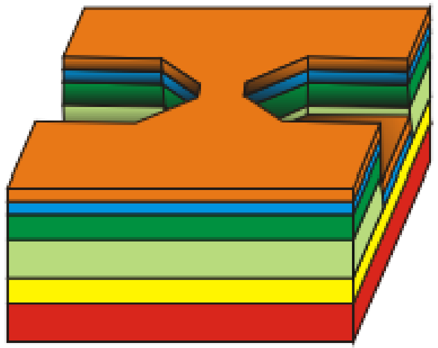
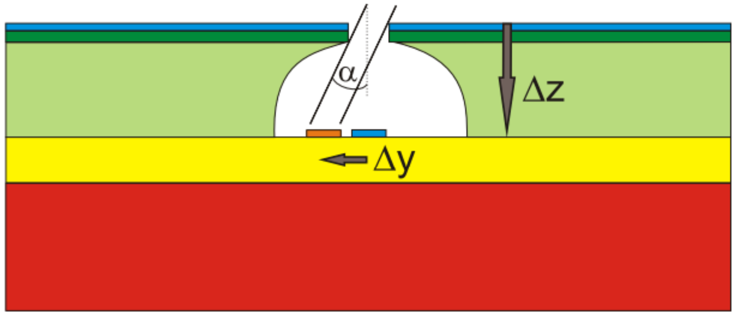
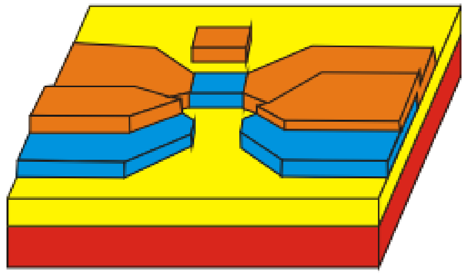
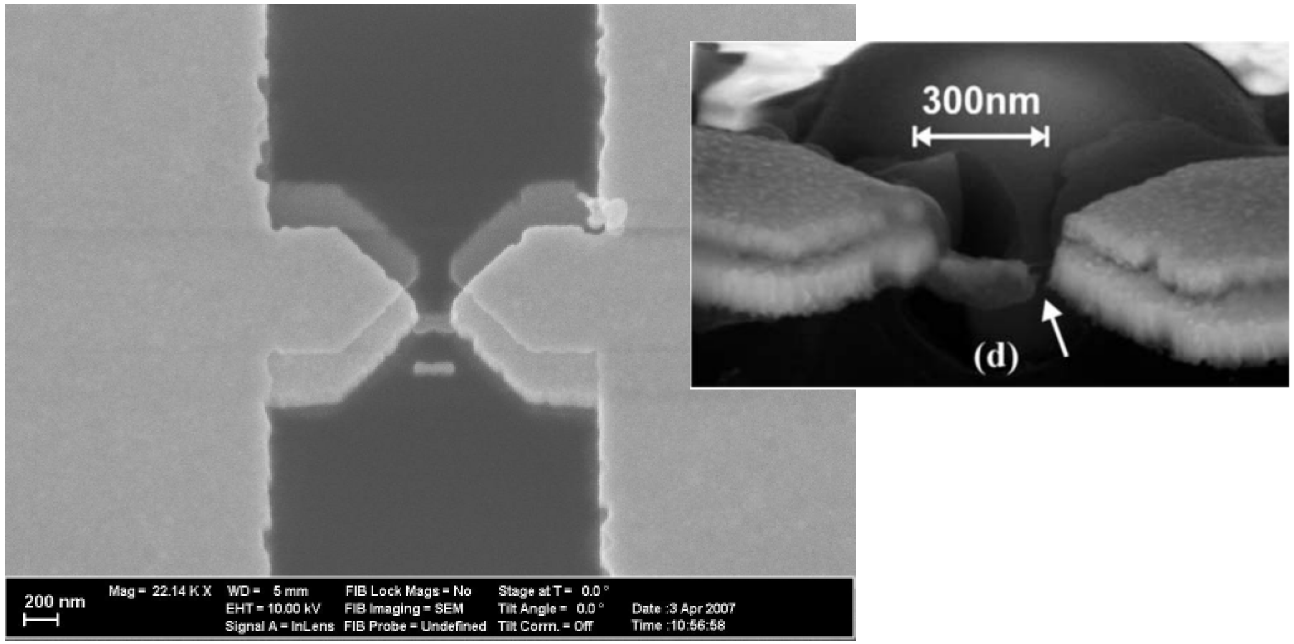
heterocontacts *via* shadow evaporation





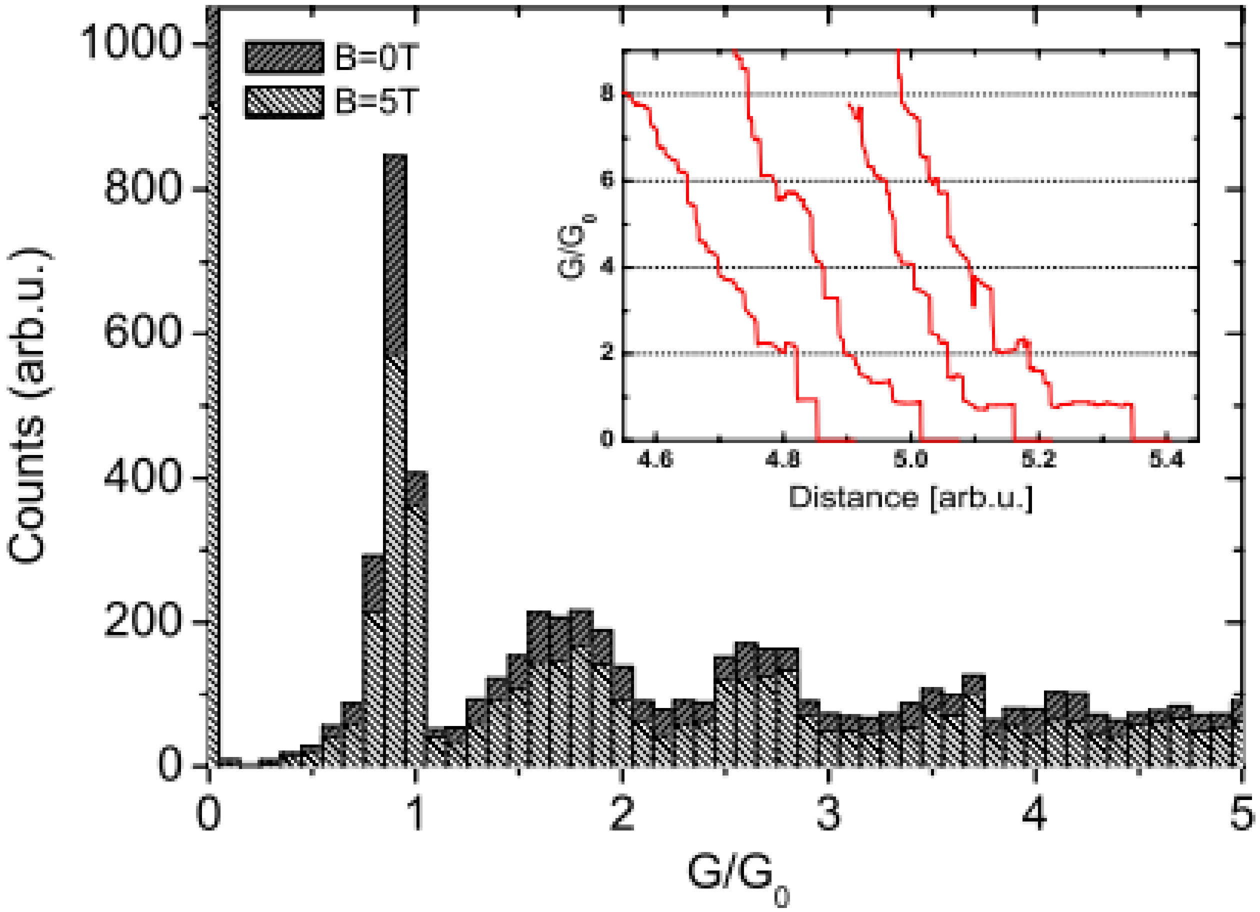




Au – Co – Au

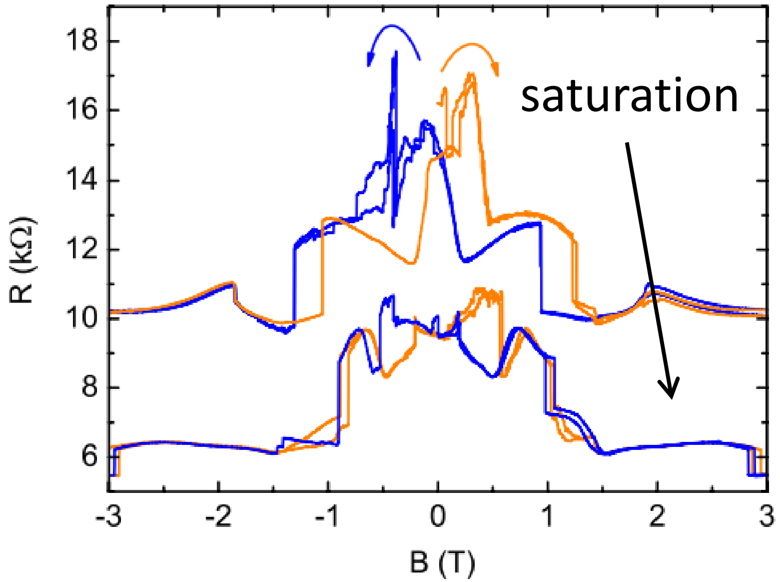
Co – Au - Co

Co-Au-Co and Au-Co-Au MCBJs



contatcs break close to the Co-Au interface
mainly Au-Au and Co-Co contacts

MR of **Co – Au – Co** MCBJs

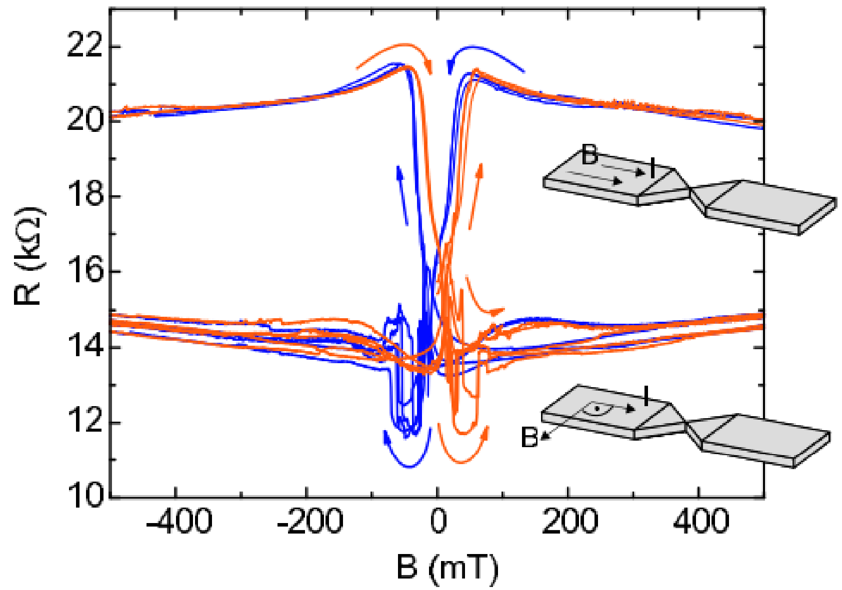


B out of plane

MRR up to 70%

complex MR behaviour, similar to Co MCBJs

Low- (B<2T) and High-field (B>2T) components

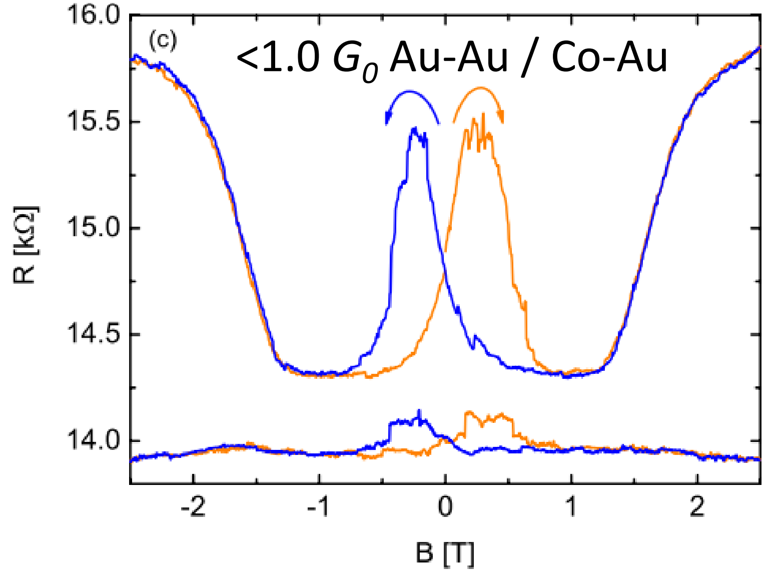


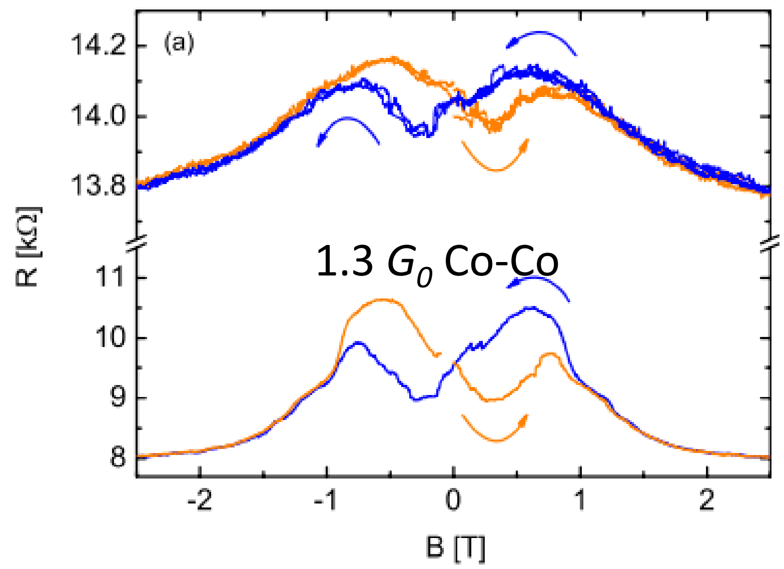
B in plane

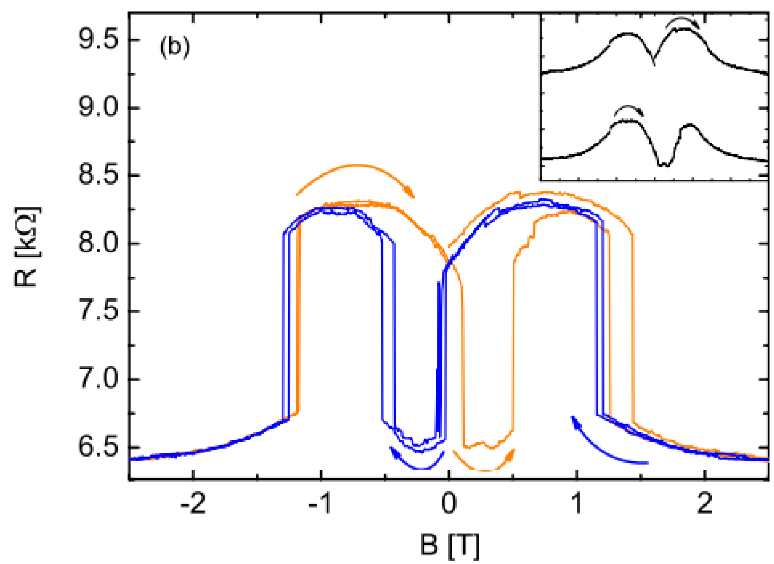
AAMR due to high spin-orbit coupling

hysteretic jumps for transversal *B*

MR of **Au – Co – Au** MCBJs







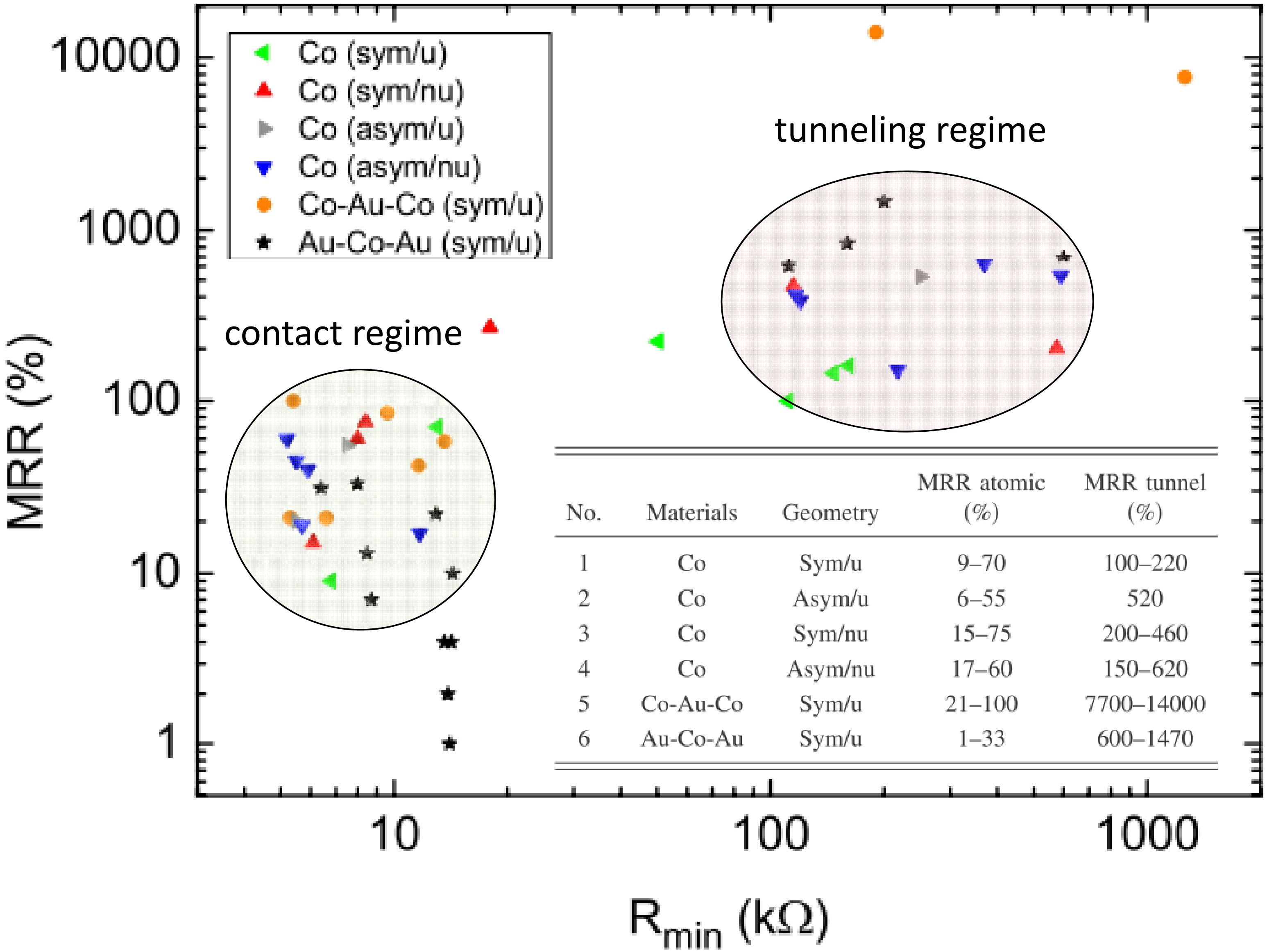
@1.0 G0 relatively low MRR (< 4%)

@1.3 G0 higher MMR (30%)

double-peak structure

hysteretic minima

occasional jumps due to field induced contact reconfiguration



No.	Materials	Geometry	MRR atomic (%)	MRR tunnel (%)
1	Co	Sym/u	9–70	100–220
2	Co	Asym/u	6–55	520
3	Co	Sym/nu	15–75	200–460
4	Co	Asym/nu	17–60	150–620
5	Co-Au-Co	Sym/u	21–100	7700–14000
6	Au-Co-Au	Sym/u	1–33	600–1470

Au / Co Heterocontacts

- large XMR up to 100% in atomic contact, 15000% in tunneling regime

- ***disentangle contribution of leads at atomic-size constriction***

- ***GMR / TMR*** effect due to ferromagnetic leads

- no signature of BAMR

-strong ***AAMR*** in all samples

- magnetostriction important only in tunneling regime

Summary

- magnetic single-atom contacts display large XMR values in simple systems

- even materials not prone to magnetism in bulk show “magnetic properties “ at the atomic scale

- homogeneous systems are “better” than heterocontacts

- origin of MR effects is manifold (GMR, TMR, AMR, AAMR … and much more)

- there are many open questions, e.g. local magnetic moment and spin-polarisation in mono-atomic Pt chains

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