Nanospintronics

"The emerging field of Quantum Spintronics..."

Large phase coherence effects in a diluted ferromagnetic semiconductor, GaMnAs

R. Giraud
&
Phynano Team @ CNRS-LPN

***coll*: B. Barbara , CNRS-LLN**

Outline

- ✓ The **'NanoGamnas'** project @ **LPN**
- ✓ Phase-coherent spin transport in a ferromagnet

Mesoscopic physics ↔ Spintronics

✓ The **'NanoGamnas'** project @ **LPN**

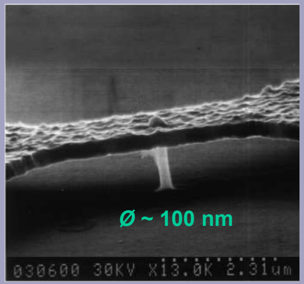
Phase-coherent manipulation of a localized (i) or a delocalized (ii) spin

This research contributes to make a link between spintronics and mesoscopic physics

It is based on all-semiconducting materials,
and uses an epitaxial ferromagnet GaMnAs,
eventually integrated onto a conventional semiconducting heterostructure

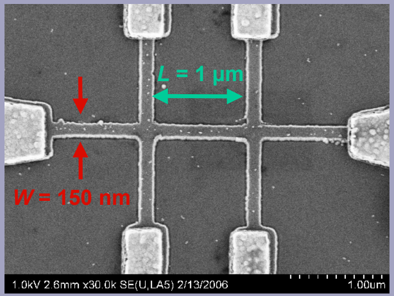
i) Spin-SET , Spin Qu-bit

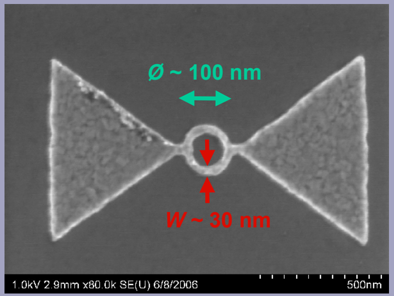
All-electrical control of the two spin-states of a single electron spin localized in a vertical quantum dot



ii) Coherent spin transport

Phase-coherent control of a spin current in a ferromagnet or a 2DEG





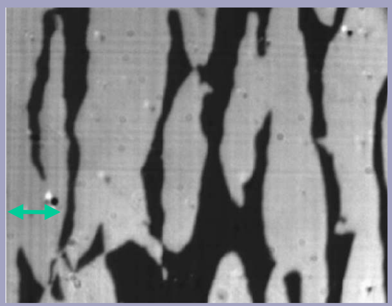
✓ The 'NanoGamnas' project @ LPN

GaMnAs

MBE-Growth

A. Lemaître, L. Thevenard

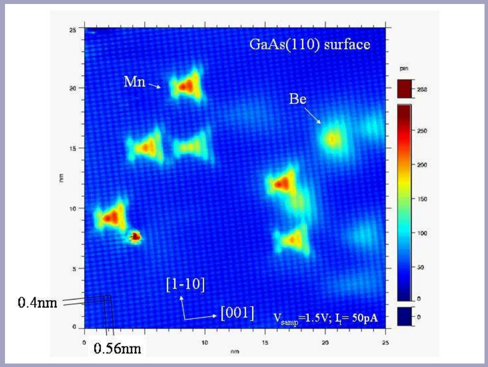
w ~ 30 µm



Coll.: J. Ferré, N. Vernier LPS-Orsay

Low-T UHV-STM

J.-C. Girard, Z. Zhang



Nanofabrication
(clean room ~ 1200 m²)

& *Mesoscopic transport*

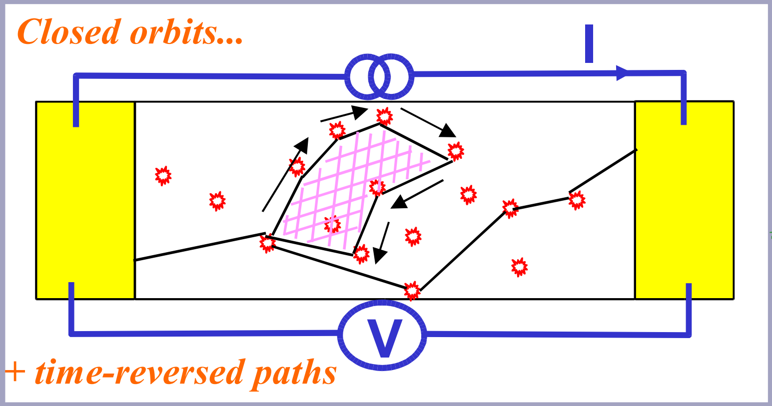
R. Giraud, L. Vila, F. Pierre, J. Dufouleur, C. David, D. Mailly, G. Faini

Ebeam lithography
1 JEOL 5DIIU 50kV nanowriter
1 LEICA 5000+ 100kV nanowriter
NanoFIB 30keV, 5nm resolution nanowriter
AFM lithography
UV lithography 4 aligners

Etching
3 RIE + 1 ICP + 1 RIBE: SF6, SiCl4, BCl3, CH4, Ar, H2, CHF3, O2
Metals and dielectrics depositions
7 chambers: Joule effect, e-beam, RF, PECVD
Thermal treatments and epitaxial soldering
Scanning electronic microscopy
2 FEG Hitachi S800 and S4800 ; 2 LaB6 and W e-gun
Standard characterization and Chip mounting
Optical microscopes, Dektak, FTIR, P(I), I(V), 4 bounding stations

✓ Mesoscopic transport & Magnetism

Quantum corrections to the conductance as a probe of L_φ



▲ *Saturation of L_φ*

due to magnetic impurities in a metal

-see F. Pierre et al., PRB 68, 085413 (2003)-

Exchange 'field' to freeze single-spin fluctuations

…but only ultra-short L_φ were reported to date, probably due to a short inelastic mean free path

-Jaroszynski et al. 95', Aprili et al. 97', Lee 04', Saito et al. 05'-

▲ *How to preserve phase coherence in a ferromagnet ?* → *reduce spin-flip scattering…*

Anisotropy 'field' to freeze low-energy spin waves fluctuations ↳ *large L^{inel}*

Epitaxial ferromagnet to avoid low-energy spin fluctuations at grain boundaries

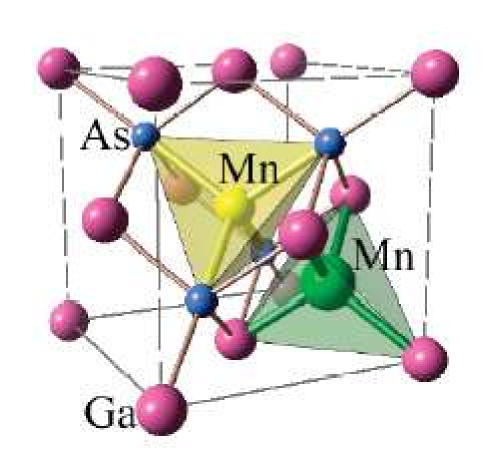
▲ *Reduced role of the spin-orbit interaction :*

$$1/\tau_\uparrow = 1/\tau_0 + 1/\tau_{so\uparrow}{}^{z} + 2\nu_\downarrow/\nu_\uparrow\ 1/\tau_{so\uparrow}{}^{x}$$

-no contribution of the anisotropic s-o interaction to the cooperon-

▲ *Internal fields…* *-Tatara & Barbara 01'/04', Dugaev & Bruno 01'-*

✓ GaMnAs : an epitaxial ferromagnet



Mn : …$3d^5 4s^2$

Ga → Mn ⇒ Mn^{2+} (S=5/2) + h

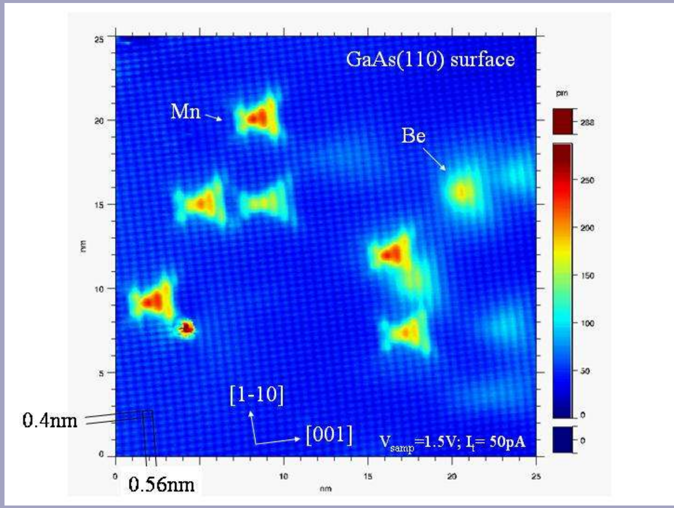
Substitutional Mn = Acceptor

Bound magnetic polaron

⇓

Impurity band / Mobility edge

Delocalized hole-induced ferromagnetism



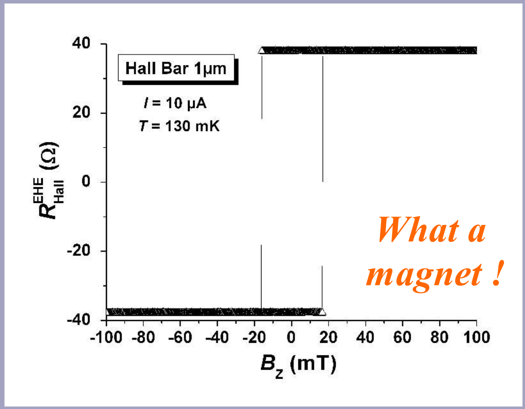
J.-C. Girard, LPN

MBE-growth engineering of the anisotropy

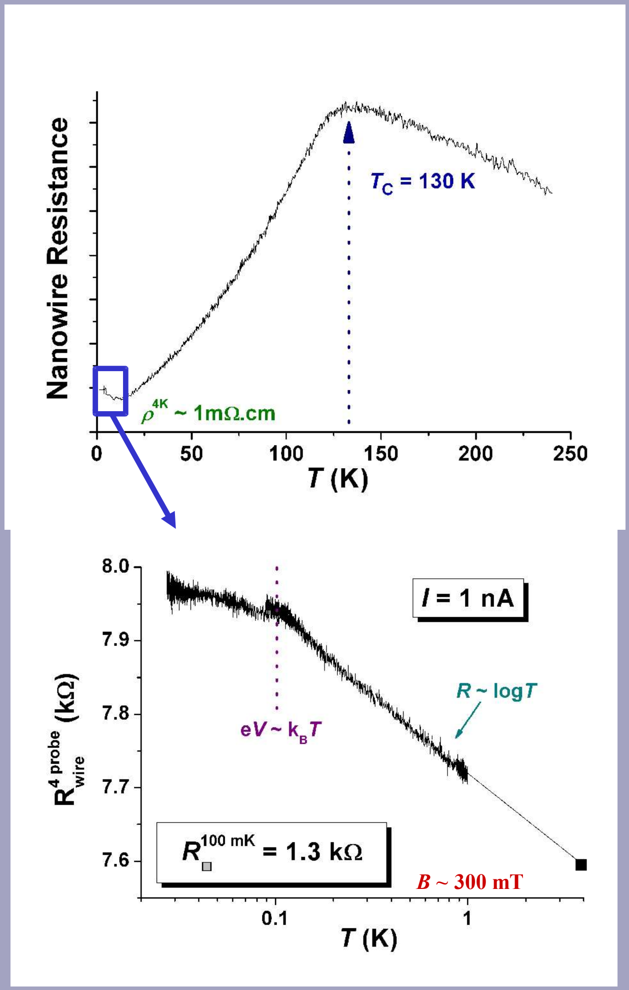
Tailored by the strains induced by the substrate on the epilayer

GaMnAs/*GaAs* : *In-plane* anisotropy

GaMnAs/*InGaAs* : *Out-of-plane* anisotropy ⟶



✓ Phase coherence in GaMnAs



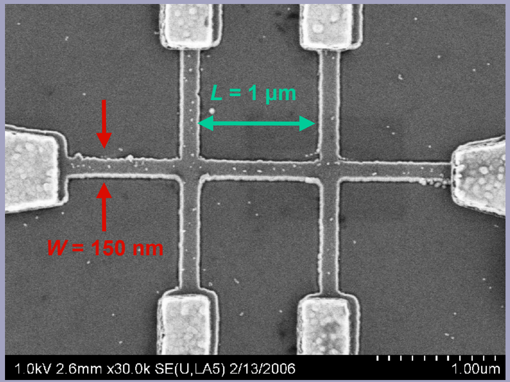
Metallic behavior!

g ~ 26

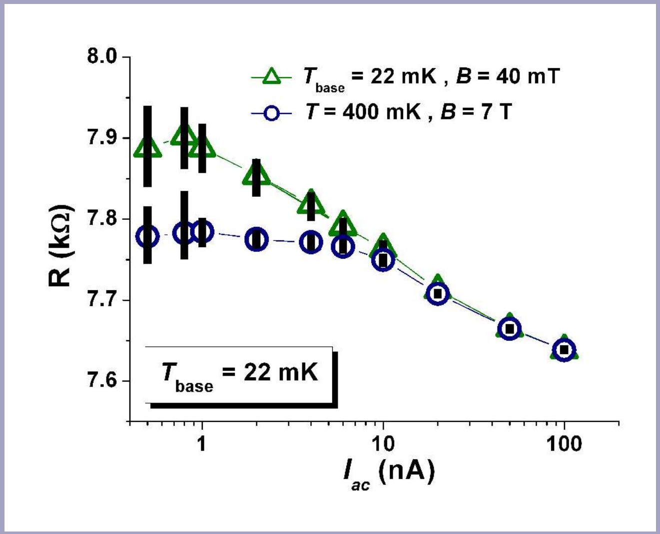
ρ ~ 1 mΩ.cm

p ~ 5.10^{20} cm^{-3}

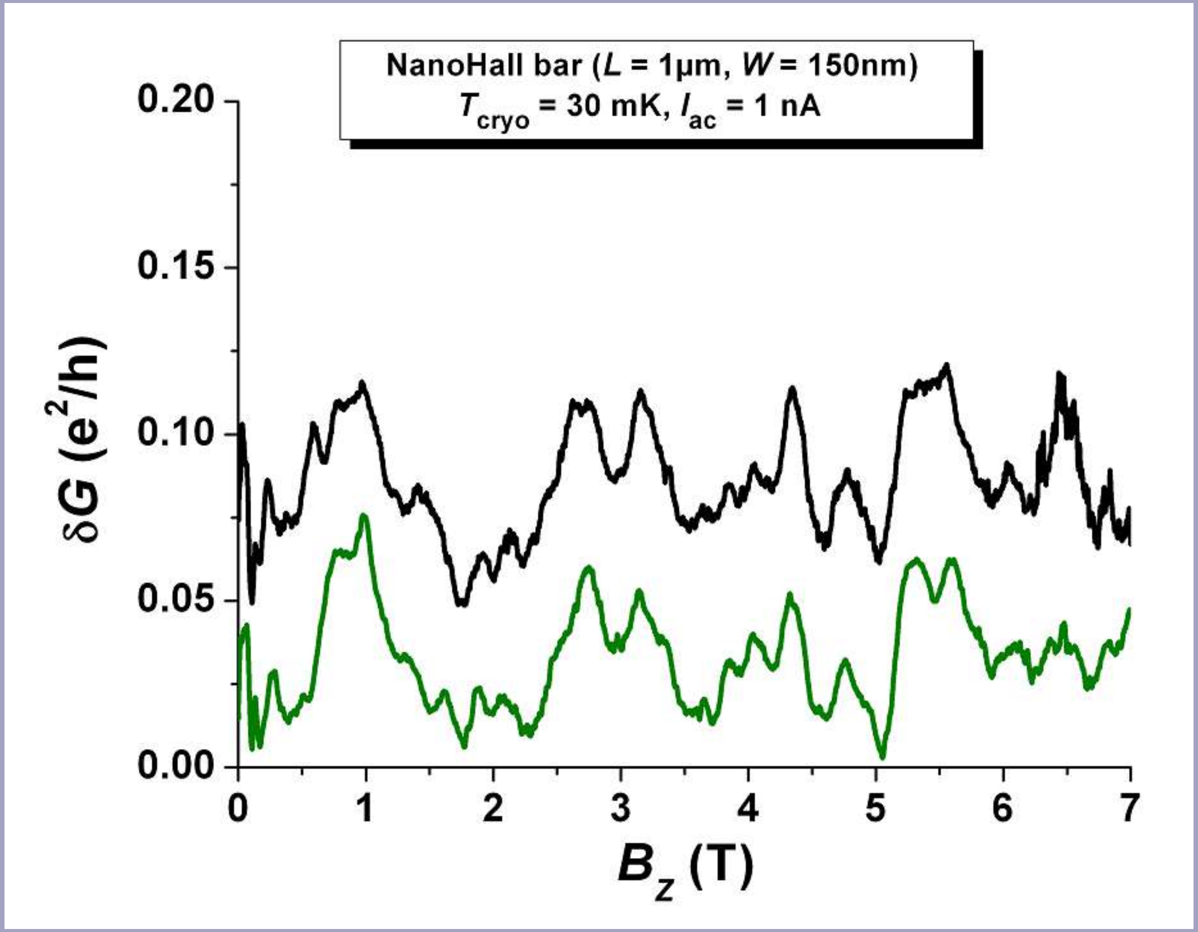
D ~ 1 cm^2/s



Coulomb interaction in 2D ?

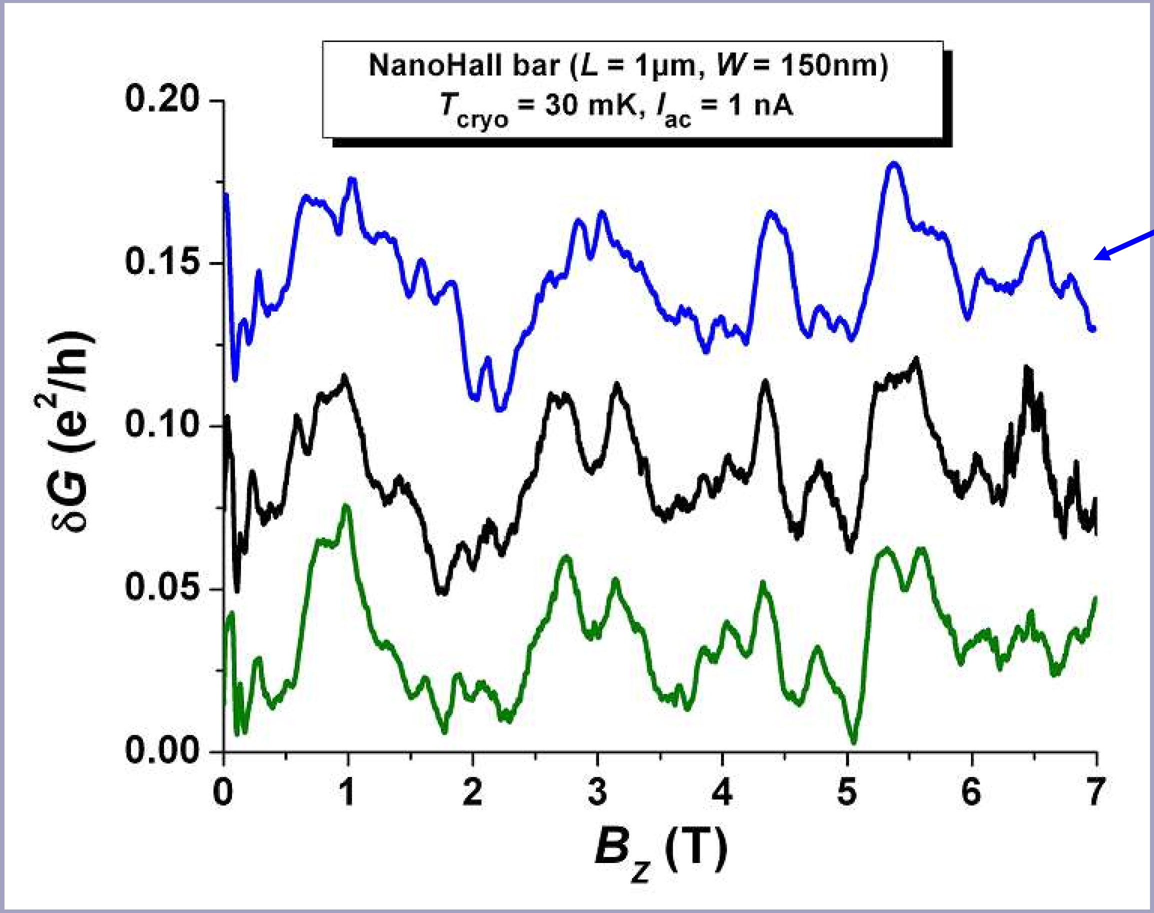


✓ Phase coherence in GaMnAs



→ Reproducible aperiodic universal conductance fluctuations

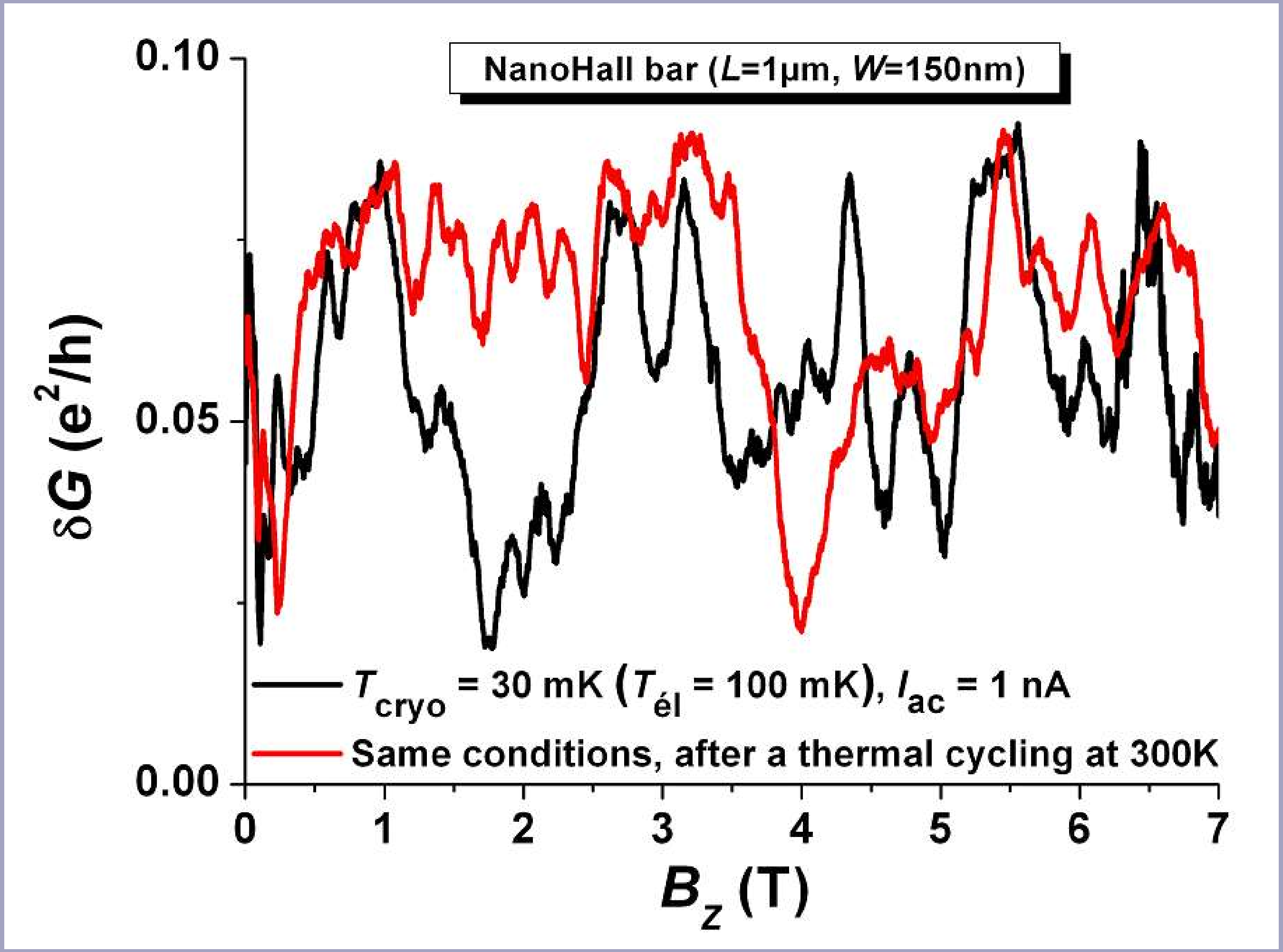
✓ Phase coherence in GaMnAs



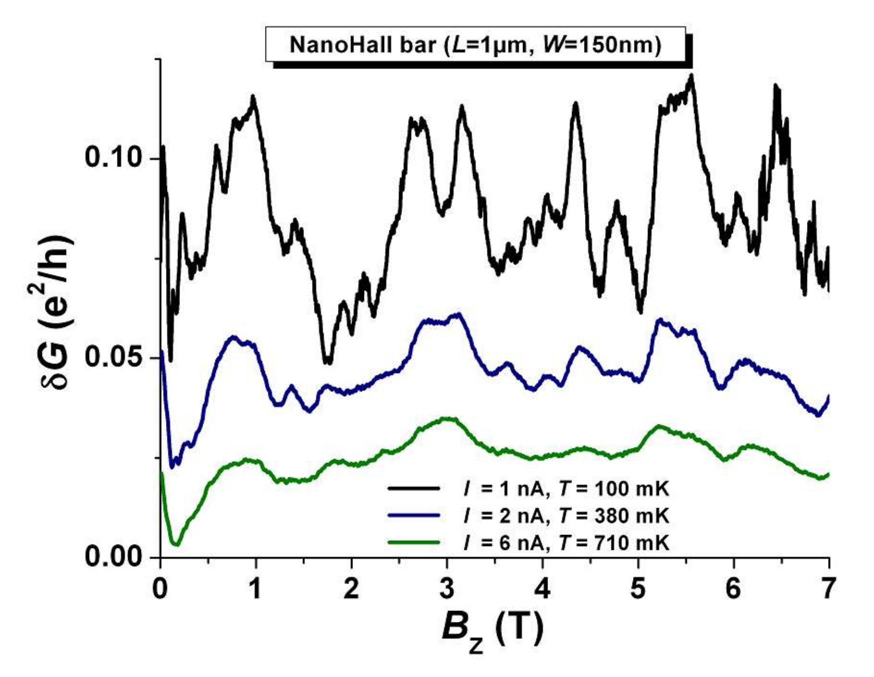
Warming to 4K during the WE ?

→ Exact nature of the fluctuators at large fields ?....

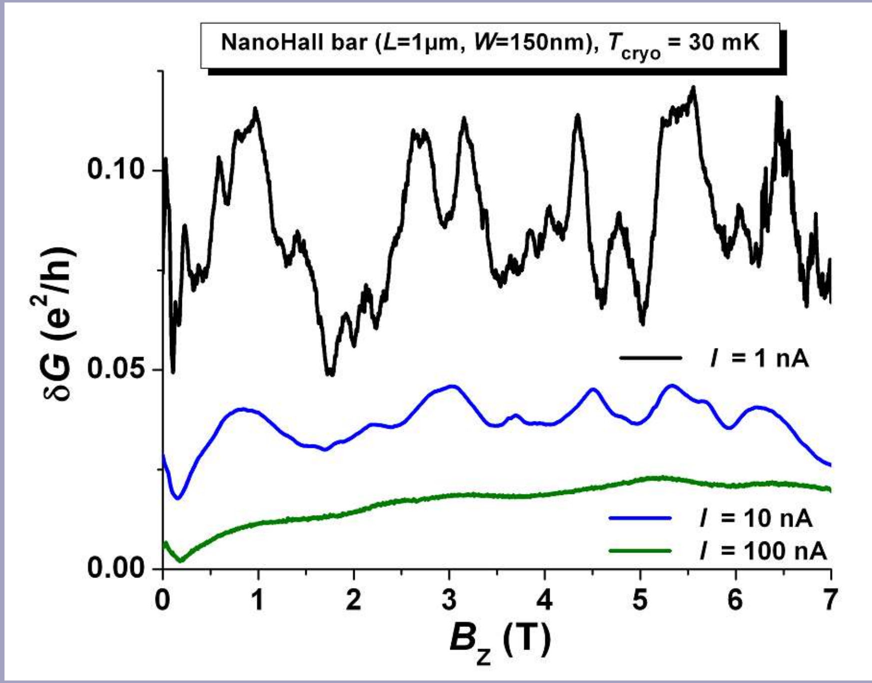
✓ Phase coherence in GaMnAs



✓ Phase coherence in GaMnAs

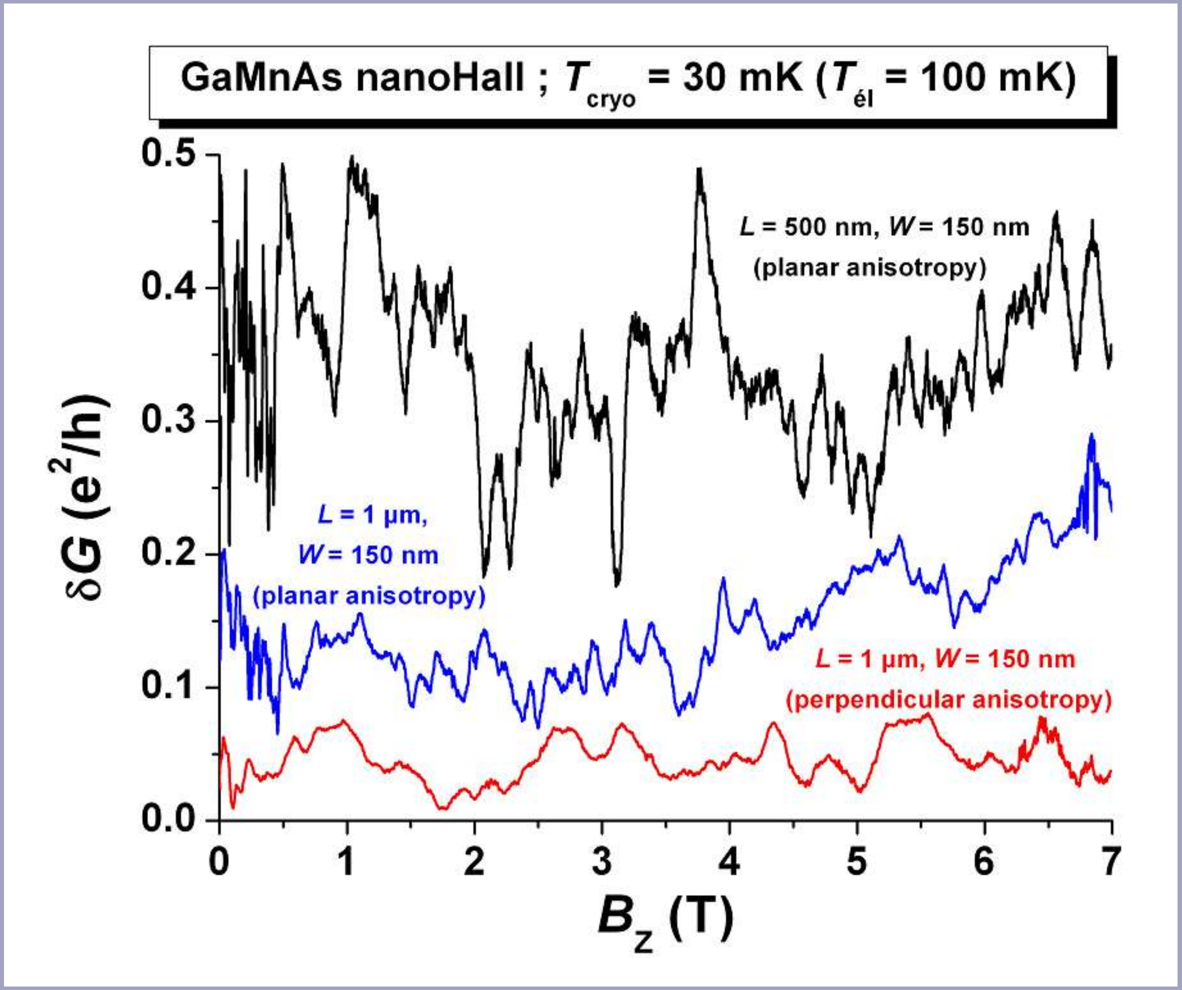


Temperature dependence of UCF



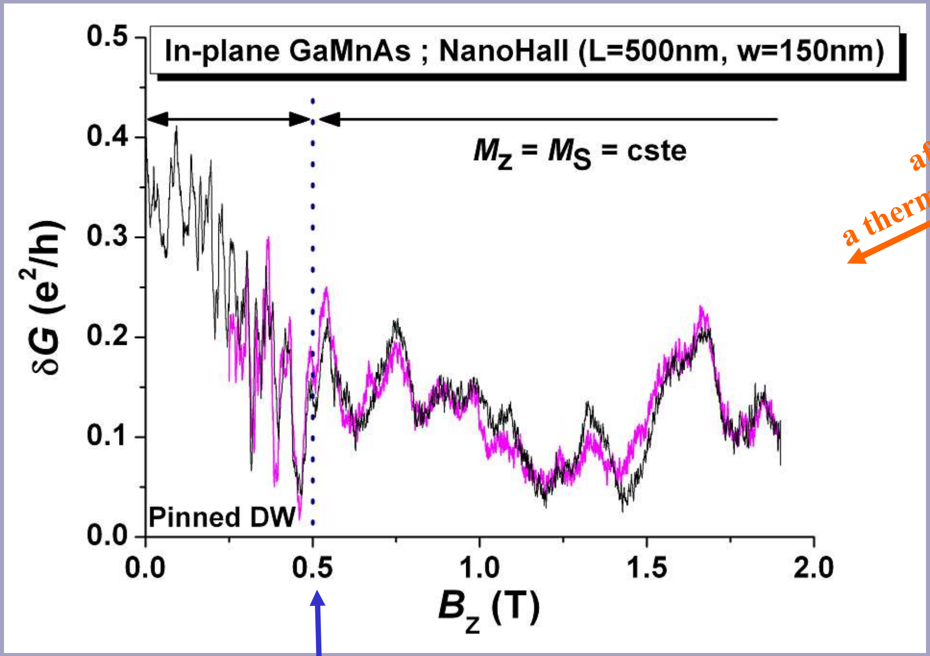
Bias dependence of UCF

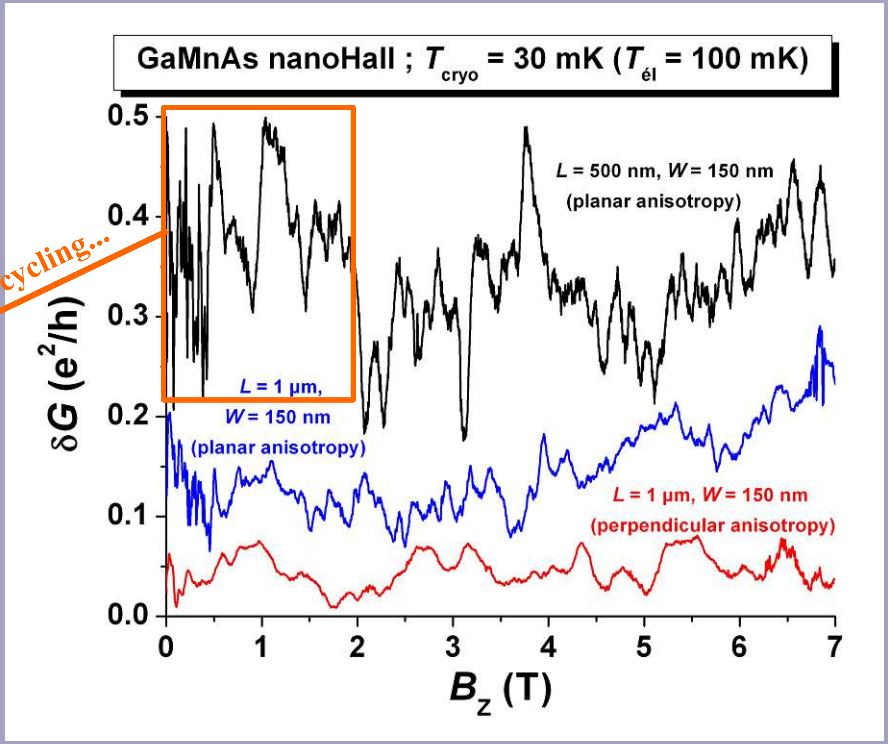
✓ ***Planar*** vs. ***Perpendicular*** anisotropy



→ Partial failure of the semi-classical approximation...

✓ ***Planar*** vs. ***Perpendicular*** anisotropy





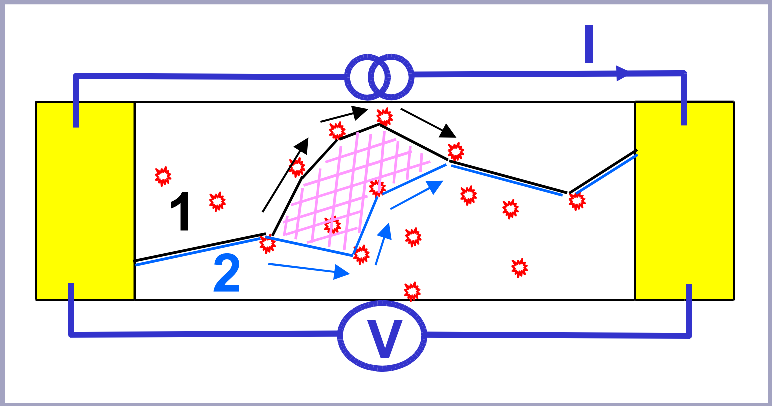
after a thermal cycling...

AMR saturation field H_A

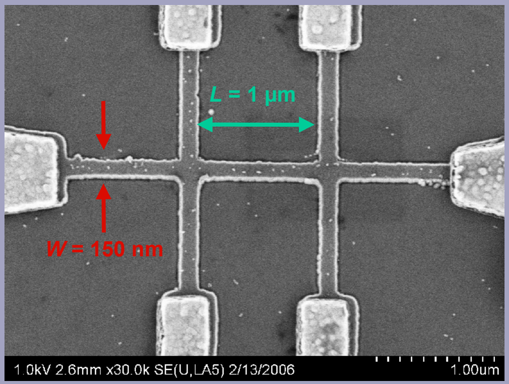
→ $H_Z < H_A$: Onset of coherent scattering by Domain Walls

✓ Phase coherence in a ferromagnet

Universal Conductance Fluctuations as a probe of L_φ



→ **Aperiodic conductance fluctuations**



***Effective* phase coherence length**
extracted from UCF within the framework
of the semi-classical approximation…

Quasi-1D regime ($L_T > W$)

$$\delta G^{rms}\ (e^2/h) = (L_\varphi/L)^{3/2}$$

Quasi-2D regime ($L_T < W$)

$$\delta G^{rms}\ (e^2/h) = L_T/L^*(L_\varphi/L)^{1/2}$$

Large phase coherence effects in a diluted ferromagnetic semiconductor, GaMnAs

✓ Decoherence…

- ***Large effective phase coherence lengths extracted from the ½classical analysis***

L_φ ~ 100 nm @ 100mK

About three times larger than in ultra-narrow wires (reduced edge effects, material quality?)
but L_T not so accurately known
for a quantitative estimation of L_φ

- ***Mechanism for decoherence ?***

Power-law dependence of τ_φ (T)

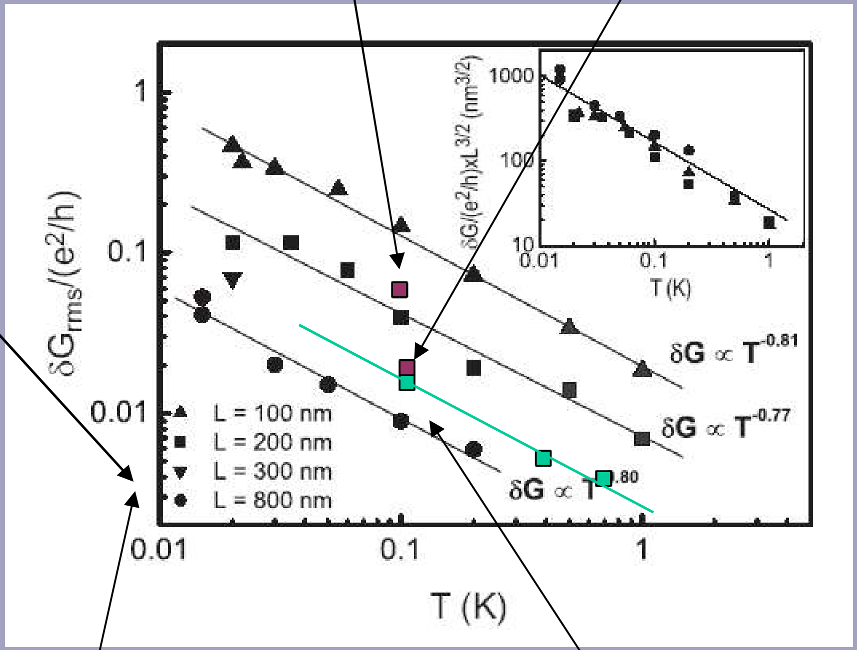
Quasi-2D regime : $\tau_\varphi (T) \sim 1/T$

Coulomb interaction …?

→ dimensional crossover to the quasi-1D regime...?

GaMnAs plan
***L* = 500 nm**

GaMnAs plan
***L* = 1 µm**



GaMnAs perp
***L* = 1 µm**

K.Wagner *et al.*, cond-mat/0603418

Summary & Conclusions

- Large quantum interference effects unambiguously observed in epitaxial GaMnAs nanowires...

  with *deviations* from a semi-classical behavior,

  as expected for GaMnAs valence subbands + $\lambda_F \sim L^{el}$

- Planar *vs*. Perpendicular anisotropy indicates that the interference patterns are dominated, as expected, by *structural disorder* but additional sources of fluctuations are also present

- Planar anisotropy study gives indications that *spin fluctuations* play a relevant role at low fields

- *More investigations are carried out...*