Aharonov-Bohm cages in AlGaAs-GaAs systems

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Lancaster meeting January 2003

Laboratory of Photonics and Nanostructures

LPN – CNRS, Route de Nozay, F – 91460 Marcoussis

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Laboratory of Photonics and Nanostructures (LPN)

Microstructures and Microelectronics Laboratory L2M (UPR20)

Active in Nanosciences since 1985

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Concepts and Devices for Photonics Laboratory CDP (URA250)

CNET 1950 (Sciences for Telecom)

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

France Telecom CNET

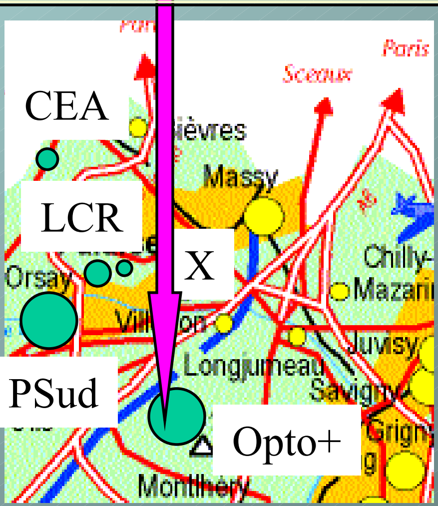
1/01/2001

24 M$

CNRS, MR, IDF, Alcatel, FT

Laboratory of Photonics and Nanostructures (UPR20)

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

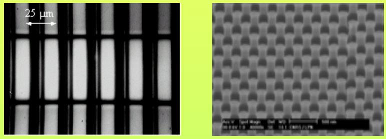


- **Located on Alcatel R&D Marcoussis Center**
- **40 permanent researchers, 40 technical staff, 20 PHDs (CNRS lab STIC+SPM)**
- **5000 m^2 with Shared Technology facilities clean rooms (700 m^2), Epitaxy (350m^2)**
- **Budget : ≅ 8 M € /year including salaries**

Research fields

Micro-fluidics

Specific nanofab,
generic tools,
biology applications

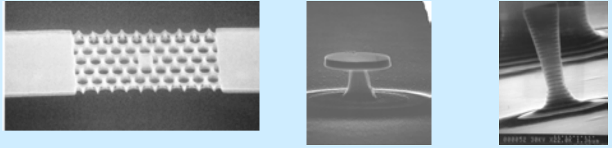


Physics of Nanostructures

lowD systems, e^- gases, quantum transport, nanomagnetism

Quantum and non linear optics

non linear PBG, cavity solitons, spontaneous emission control, quantum information, single photon sources



Nanosciences

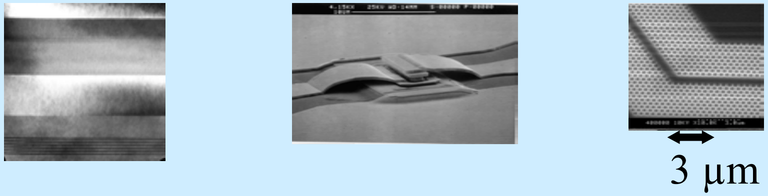
Telecom oriented basic research

Materials and technologies

New III-V materials, physics of growth and structural studies, generic and nano technologies

Advanced devices for opto-electronics

high speed sources, all optical signal processing, photonic cristals, micro-electronics, photo-detection



Nanotechnology facilities

700 m2 clean rooms

12 engineers and technicians for 7 main operations

E beam lithography

1 Jeol 5DIIU 50kV writer + new (100kV) in 2003

UV lithography

4 aligners

Metals and dielectrics depositions

7 chambers: Joule effect, ebeam, RF, PECVD

Etching

3 RIE reactors: SF6, SiCl4, CH4, Ar, H2, CHF3, O2

1 RIBE reactor: CH4, H2, Ar, O2

Nanofib

prototype 30keV, 5nm

Thermal treatments and epitaxial soldering

Scanning electronic microscopy

2 FEG Hitachi S800

2 LaB6 and W e-gun

Characterization

Optical microscopes, Dektacks, FTIR, P(I), electrical tests …

Chip mounting

3 US and thermal bounding

Epitaxy and analysis

350 m2 clean rooms

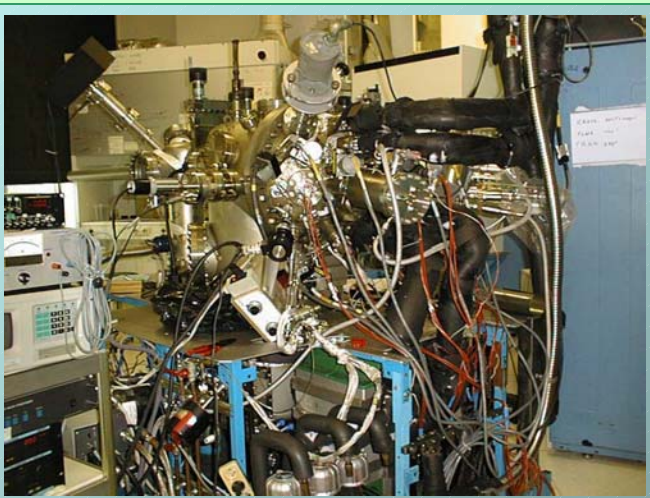
Semiconductors Epitaxy

1 MOCVD GaAs/InP

1 high purity MBE (Ga/In/Al/As)

1 multisources III-V MBE (including N , Sb)

1 gas source MBE



Analysis

STM/AFM in situ et ex situ

TEM with X analysis

FIB

2 high resolution X-ray diffraction

Raman spectroscopy

PL et PLE CW and time resolved

variable T Hall effect

low T magneto-transport

FTIR

Technology Facilities Network

- “Large” clean rooms >200 m^2
  - •4 CNRS (STIC,SPM)+Universities
  - •CEA LETI
- Funding: 100 M€ / 3 years
- 15% openness to external projects
- EC, National and CNRS priorities
  - •Biotechnologies
  - •Nanosciences/Nanotechnologies
  - •STIC

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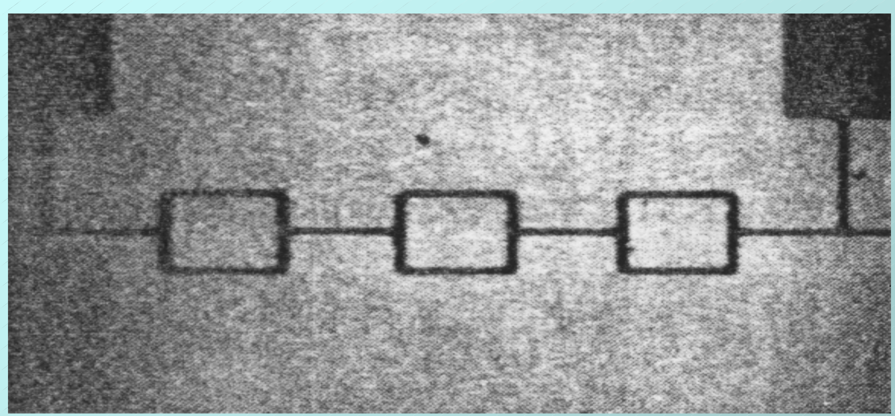
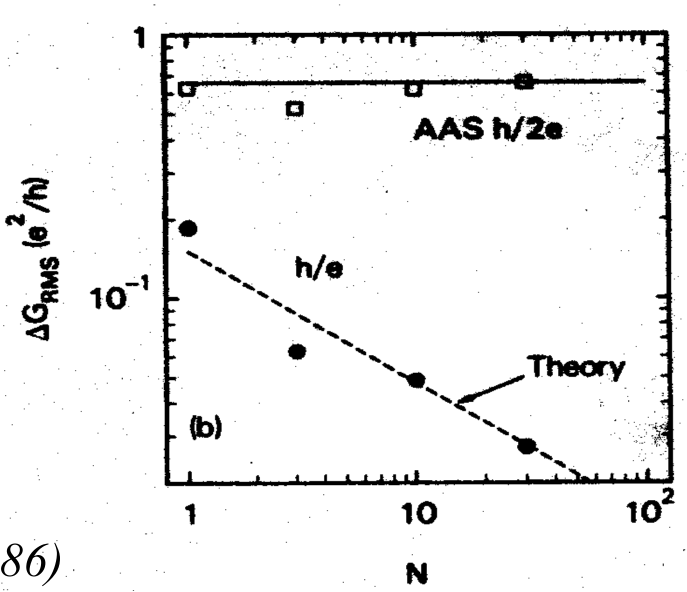
prologue

Averaging of mesoscopic effects





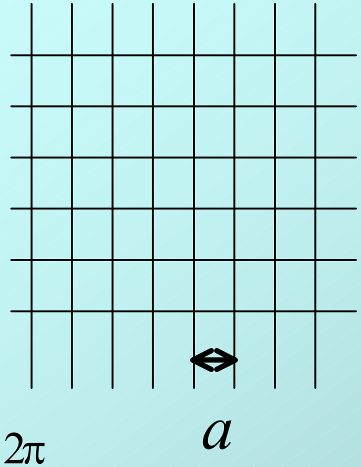
C. P. Umbach et al, Phys. Rev. Lett. , ***56****, 386(1986)*

Because of phase mixing mesoscopic effects average to zero

Weak localization is the only phase coherent process that survives to sample averaging.

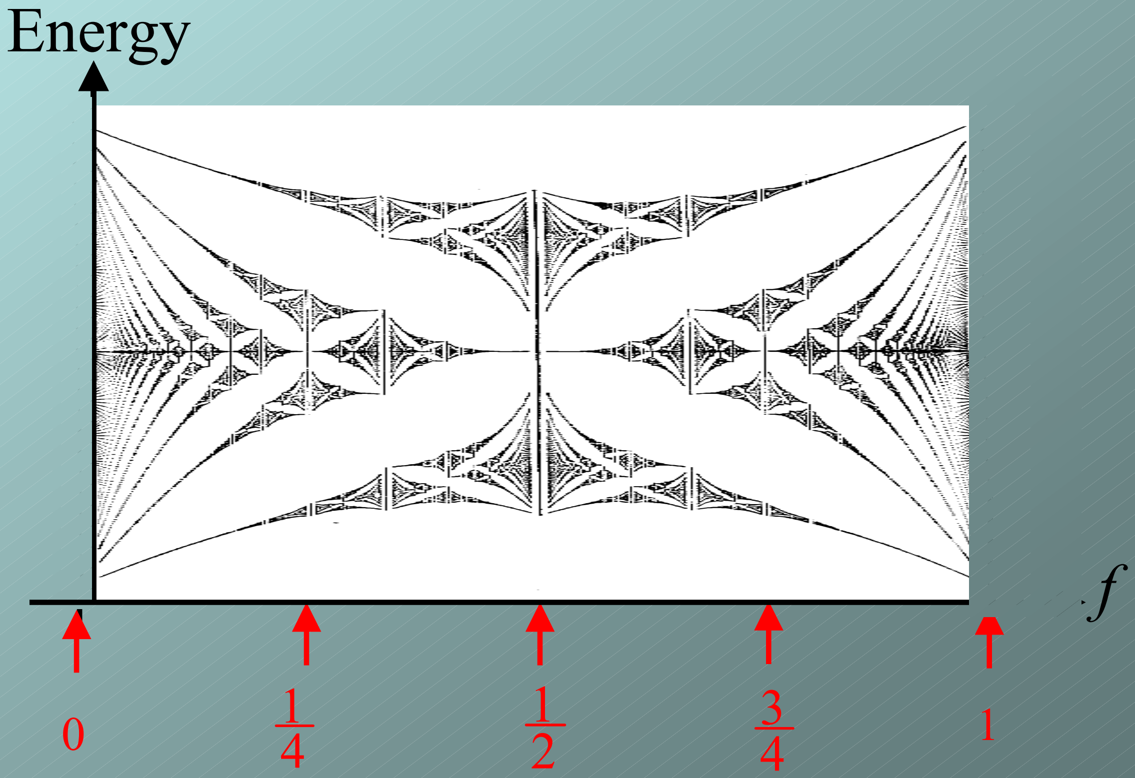
Topology can enhanced interference effects which can survive in a macrocospic sample

Energy spectrum of an electron on a square lattice in a magnetic field



$$k = \frac{2\pi}{a}$$

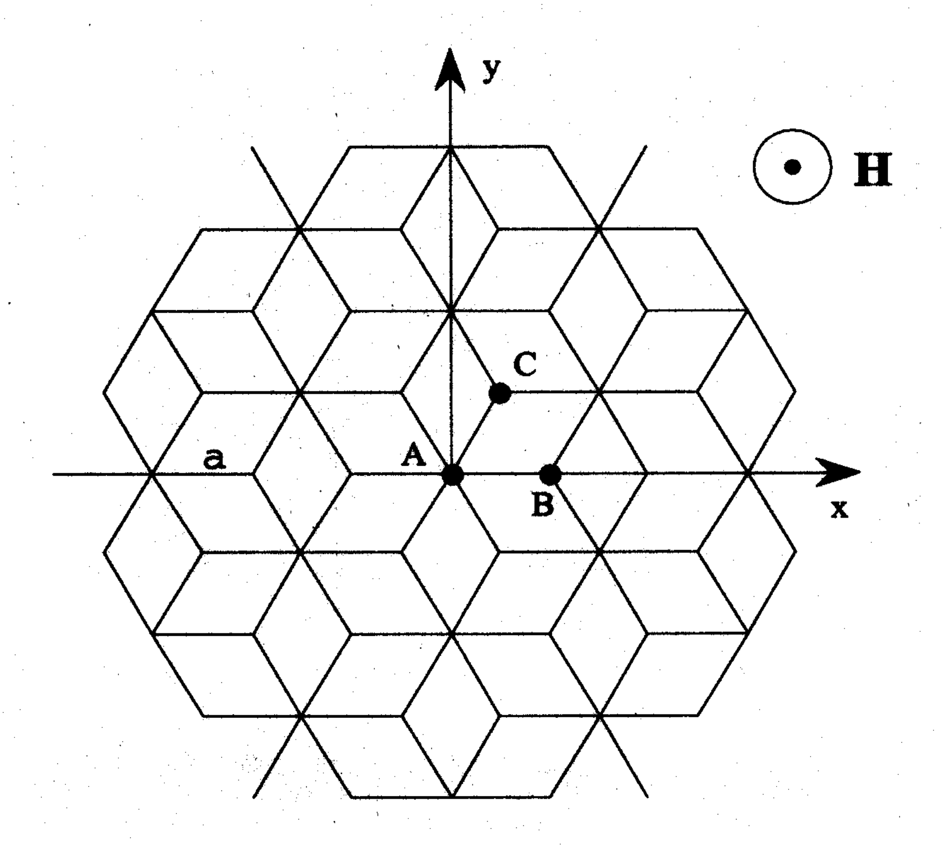
$$\left.\begin{array}{l} \omega_r \equiv \frac{v}{a} = \frac{\hbar k}{ma} = \frac{h}{ma^2} \\ \omega_c = \frac{eB}{m} \end{array}\right\} \quad f = \frac{\Phi}{\Phi_0} = \text{reduced flux}$$



For all rational values of *f*, the spectrum forms continuous bands

D. Hofstadter, Phys. Rev. B ***14****, 2239 (1976)*

The T_3 lattice



Triangular lattice with 3 sites per cell :

- Site A,6-fold coordinated
- Sites B and C, 3-fold coordinated

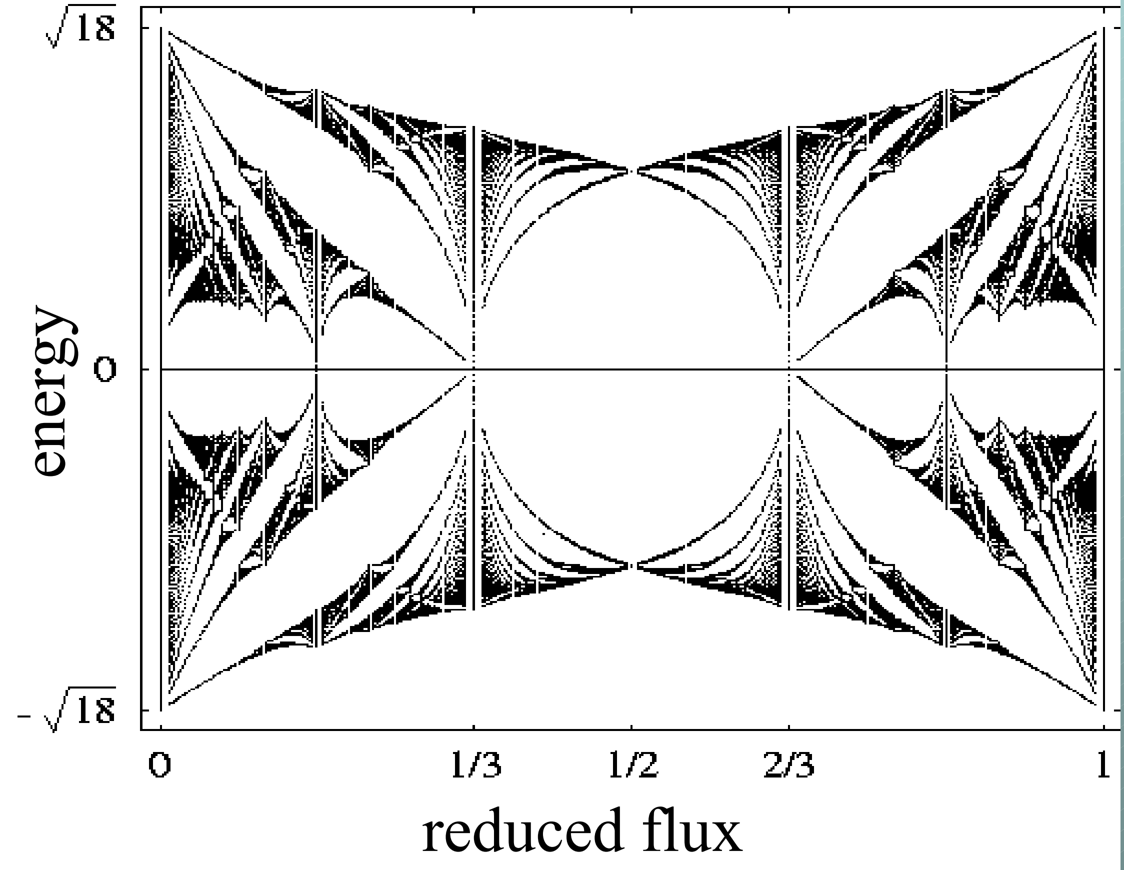
The plane is paved with rhombus

(dual of the Kagome lattice)

J. Vidal et al, Phys. Rev. Lett. , ***81****, 5888 (1998)*

Energy spectrum of theT_3 lattice

(J. Vidal, R. Mosseri, B. Douçot, Phys. Rev. Lett., 81, 5888 (1998)

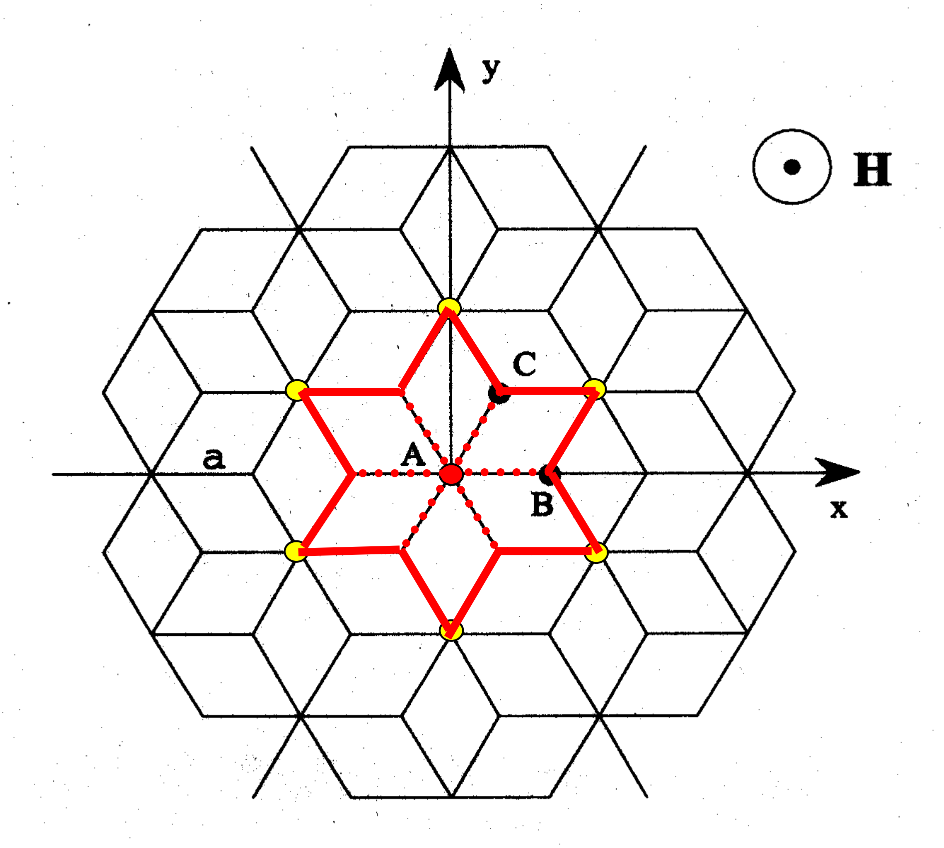


Tight binding model:
At f=1/2 , 3 degenerated levels:
The system is localized from a dynamical point of view

As the spectrum is periodic with period Φ_0 one expects the conductance to show h/e periodic oscillations

The Aharonov-Bohm cage

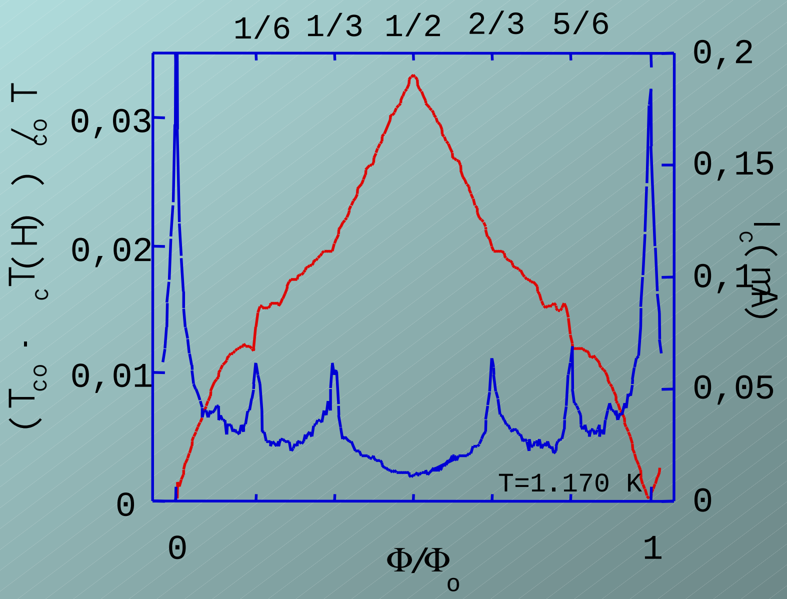
Magnetic field induced localisation phenomenon

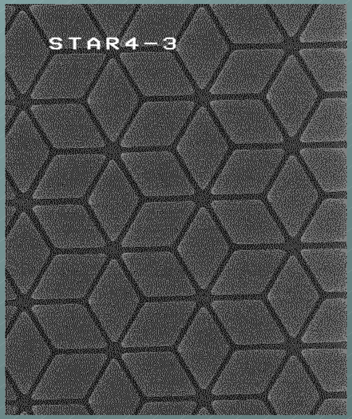


The electron wavefunction is confined inside the cage for f=1/2

Superconducting network

- Direct mapping of the GL equation and the tight-binding model
- Critical temperature of a superconducting wire network reproduces the bottom of the energy spectrum
    - Al network (LETI-PLATO)
    - 1000 x 600 µm
    - wire length = 1µm
    - wire width = 0.1 µm
    - Al thickness = 40 nm



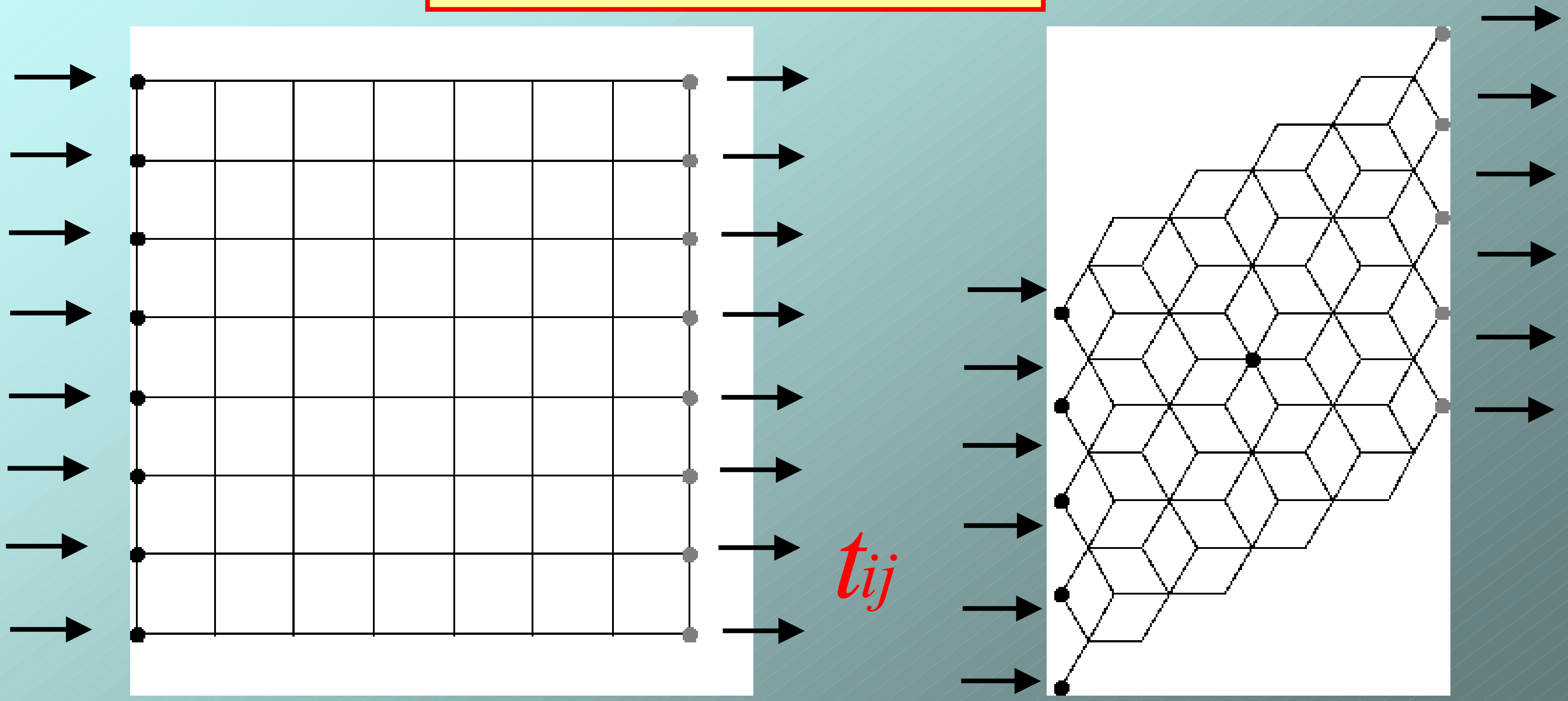


C.C. Abilio, P. Butaud, T. Fournier, B. Pannetier, J. Vidal, S. Tedesco and B. Dalzatto, PRL 83, 5102 (1999)

Does this localization effect holds for a sample where the sites are connected?

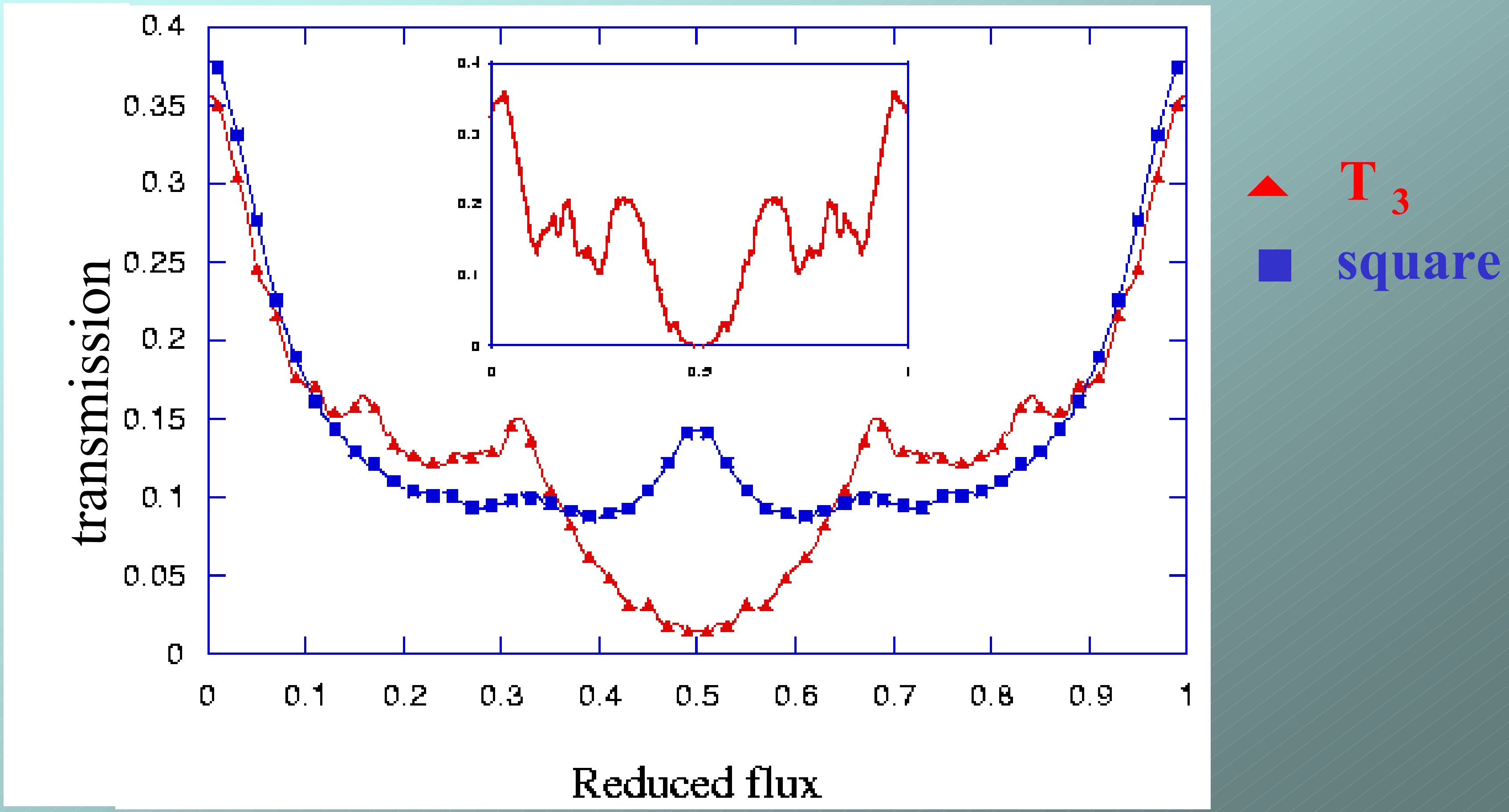
Landauer formalism

$$G = \frac{2e^2}{h} \sum_i \sum_j \left| t_{ij} \right|^2 = \frac{2e^2}{h} \times T$$



Energy averaged transmission

One channel per bond

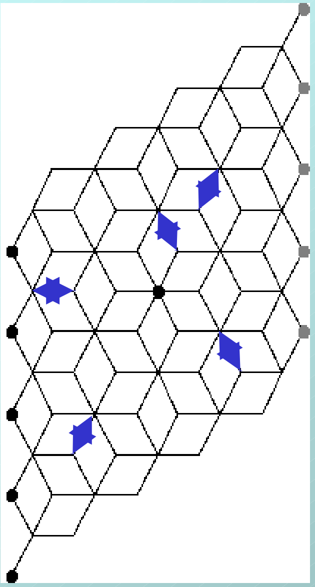


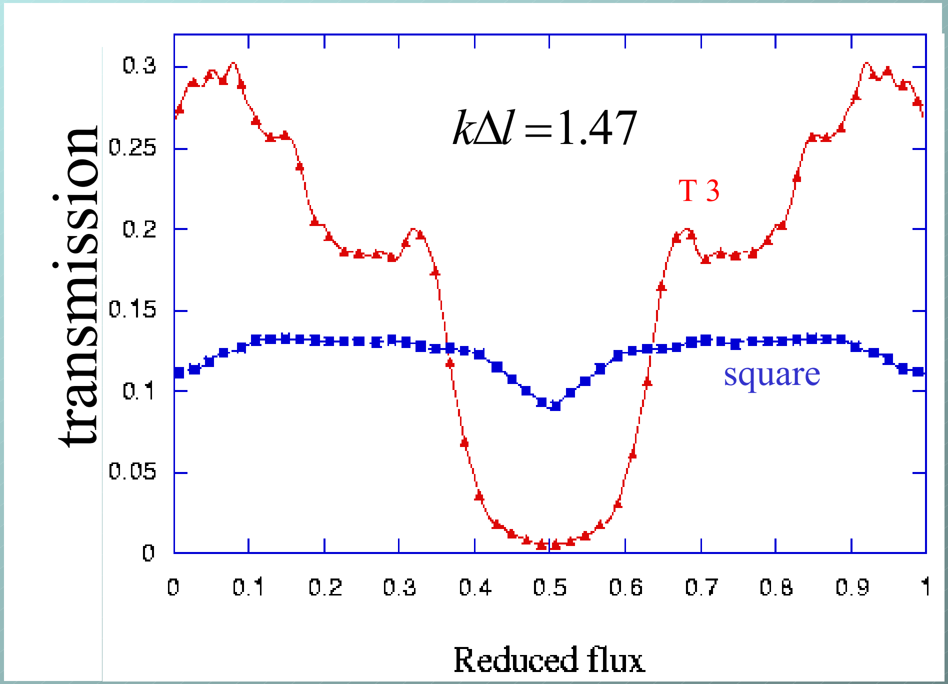
J. Vidal, G. Montambaux, B. Douçot, Phys. Rev. B62, R16294 (2000)

What about disorder?

Effect of disorder on Aharonov-Bohm cages

$k\Delta l$ ⟷ Mimic the disorder potential



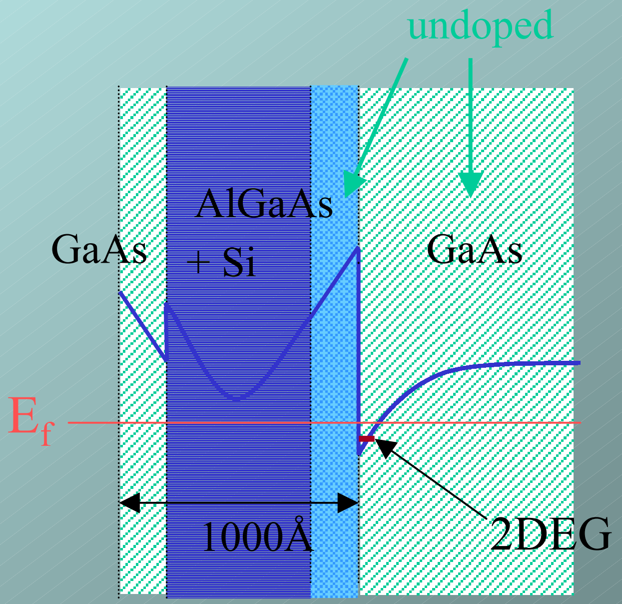


- •Weak disorder suppresses h/e periodicity for the square lattice leading to h/2e periodicity (AAS)
- •Robustness of h/e periodicity for the T3 lattice
- •Difficult to link to real disorder

T_3 lattice in the AlGaAs-GaAs system

High mobility electron gas

- Low disorder $\ell \sim 7\ \mu m$
- large phase coherence length $L_\Phi \sim 20 \mu m$
- High resistance $\delta G = -\delta R/R^2$

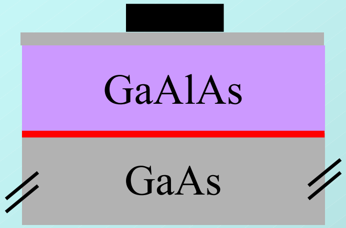


Mobility ~ 100 $m^2V^{-1}s^{-1}$
Electron density n ~ 3 10^{11} cm^{-2}
Fermi wave length ~ 60nm

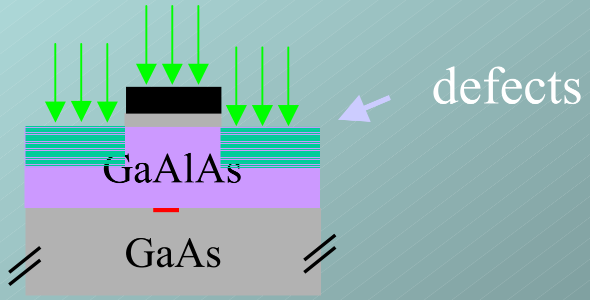
quasi ballistic regime
very weak disorder
small channel number

} **Close to theoretical models**

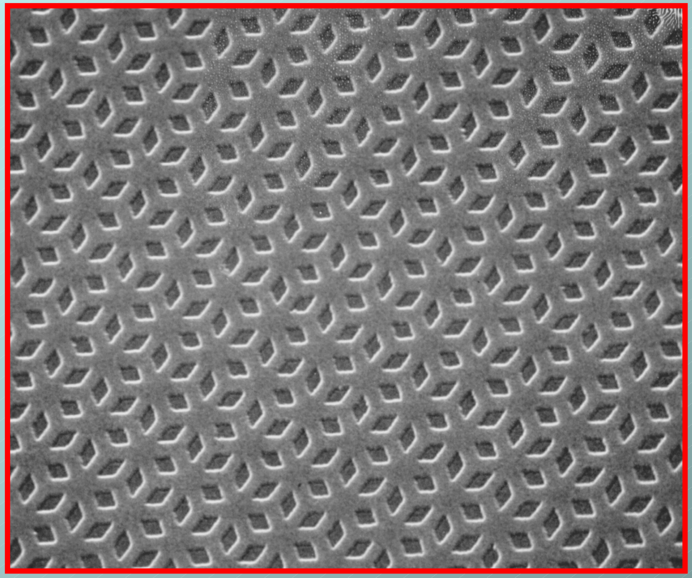
Sample processing

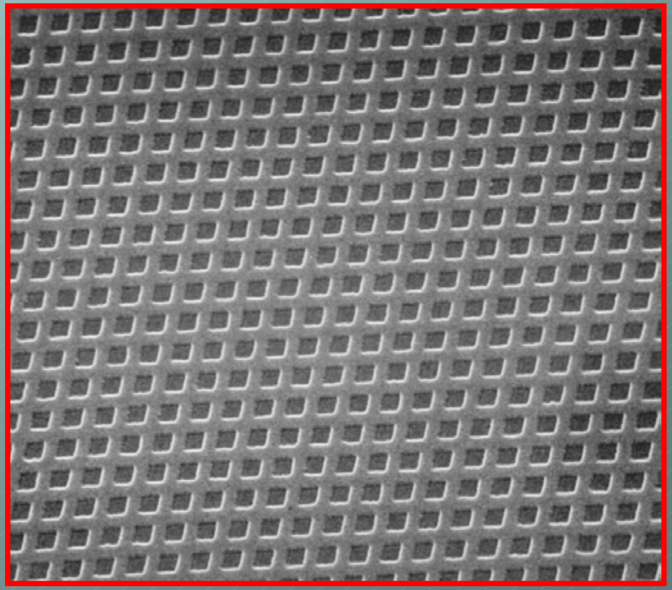


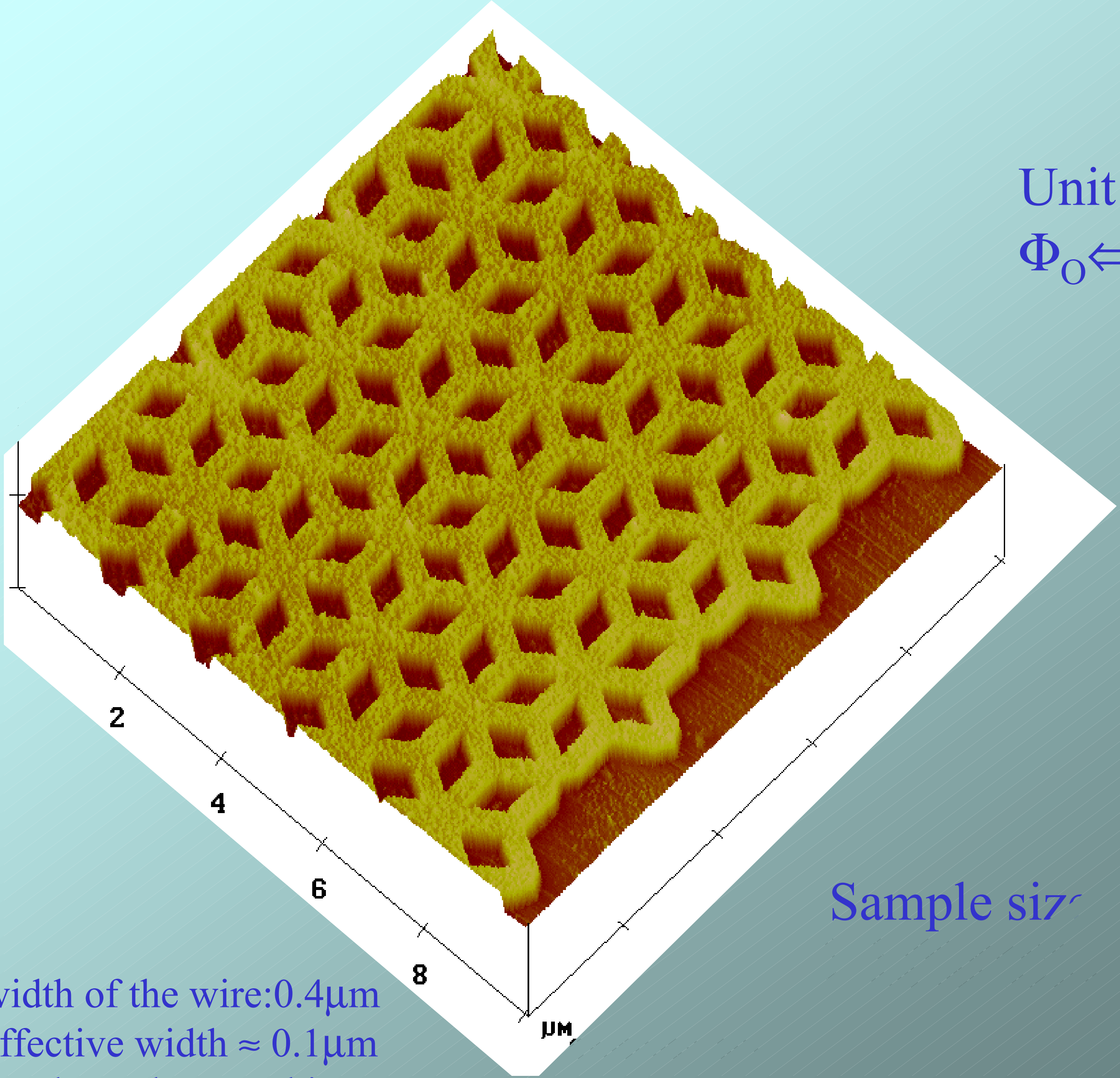
e-beam lithography
+ lift-off → Al mask



Argon ions etching







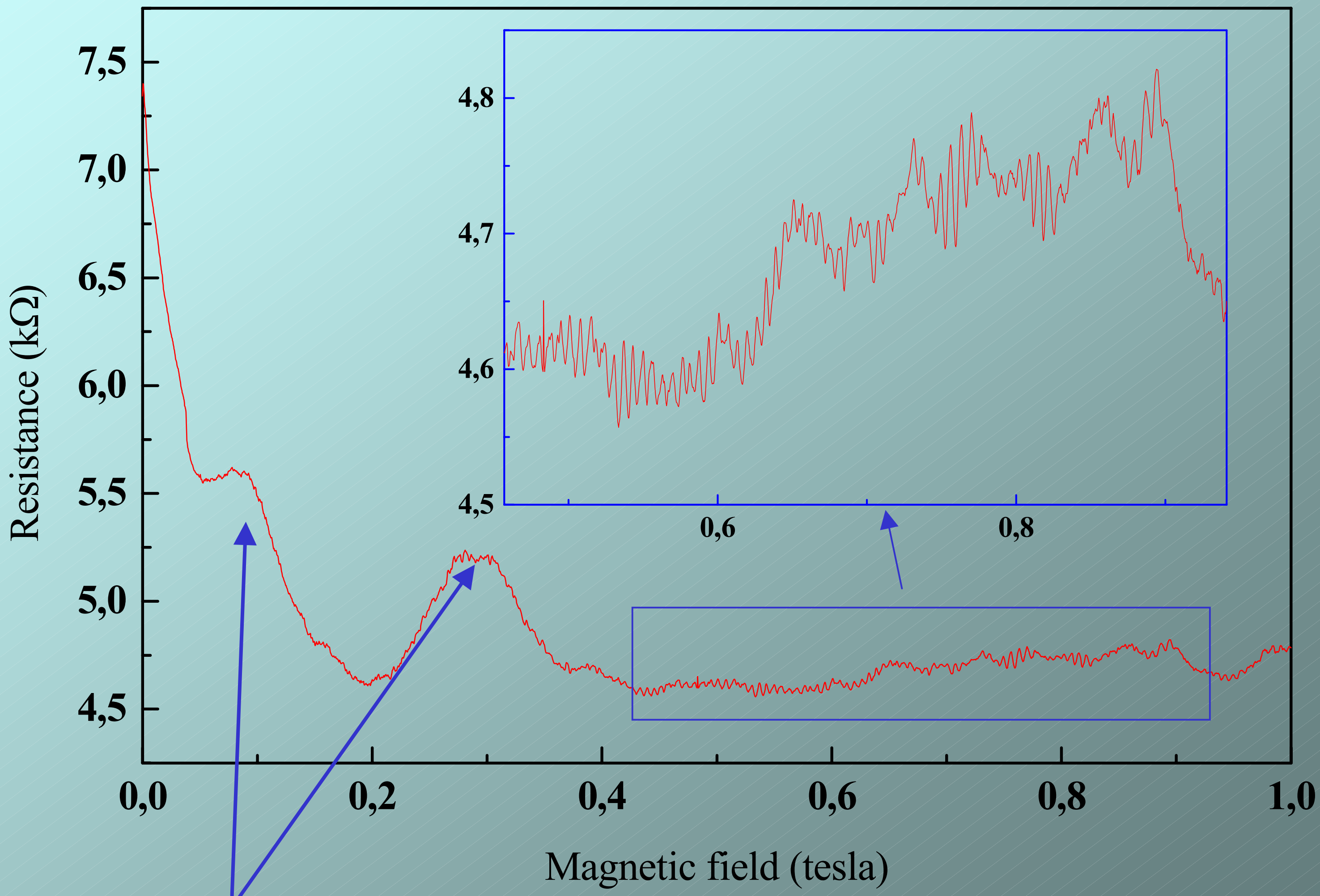
Unit cell $0.8\mu m^2$
$\Phi_O \Leftrightarrow 50G$

Sample siz bout 2500 cells

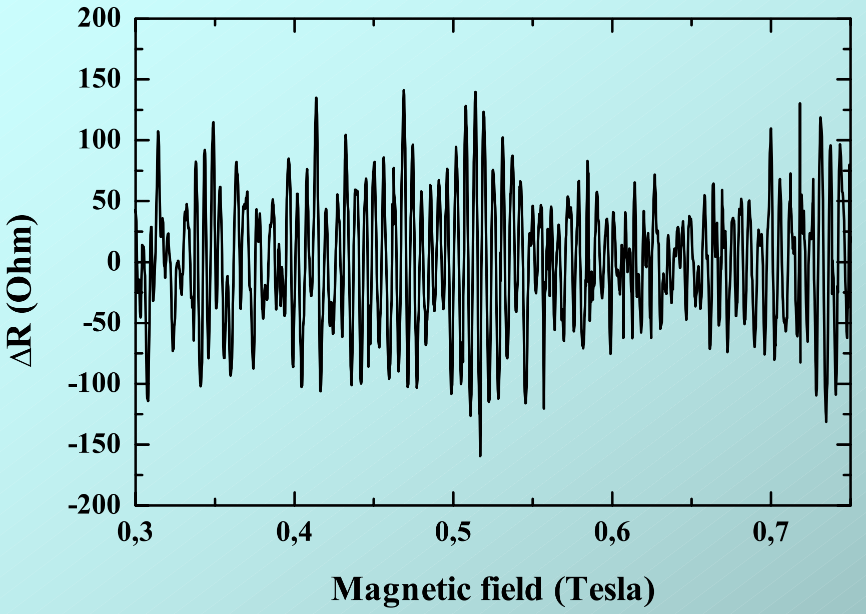
width of the wire: $0.4\mu m$
effective width $\approx 0.1\mu m$
→ depends on etching

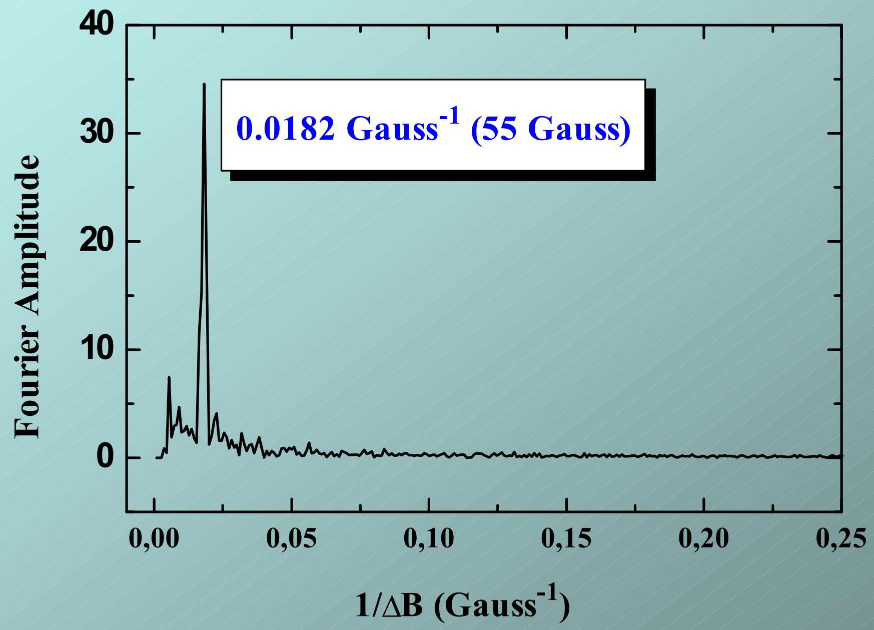
Magnetoresistance of the T_3 lattice

T=50mK



ballistic effects



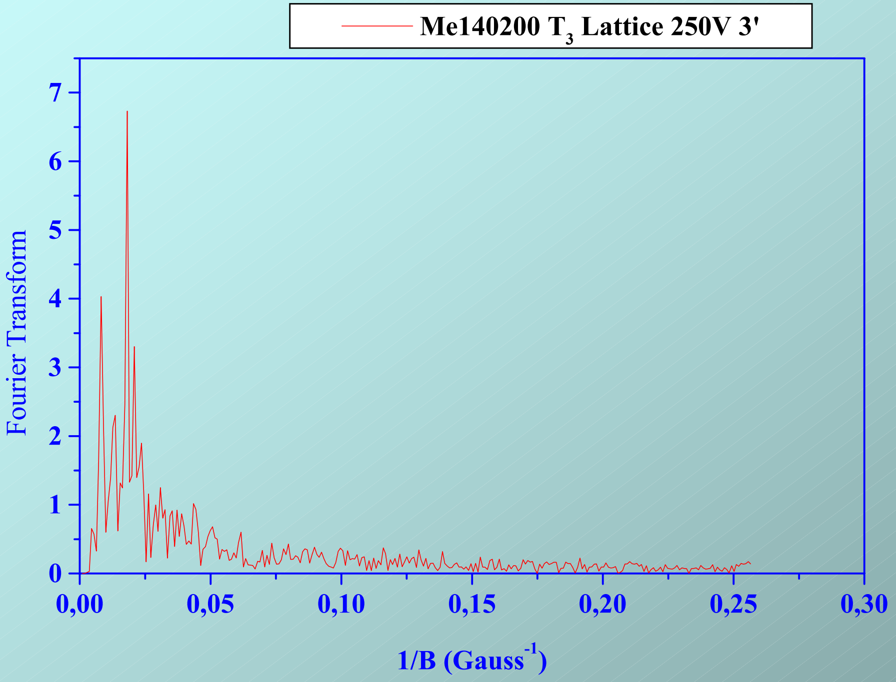


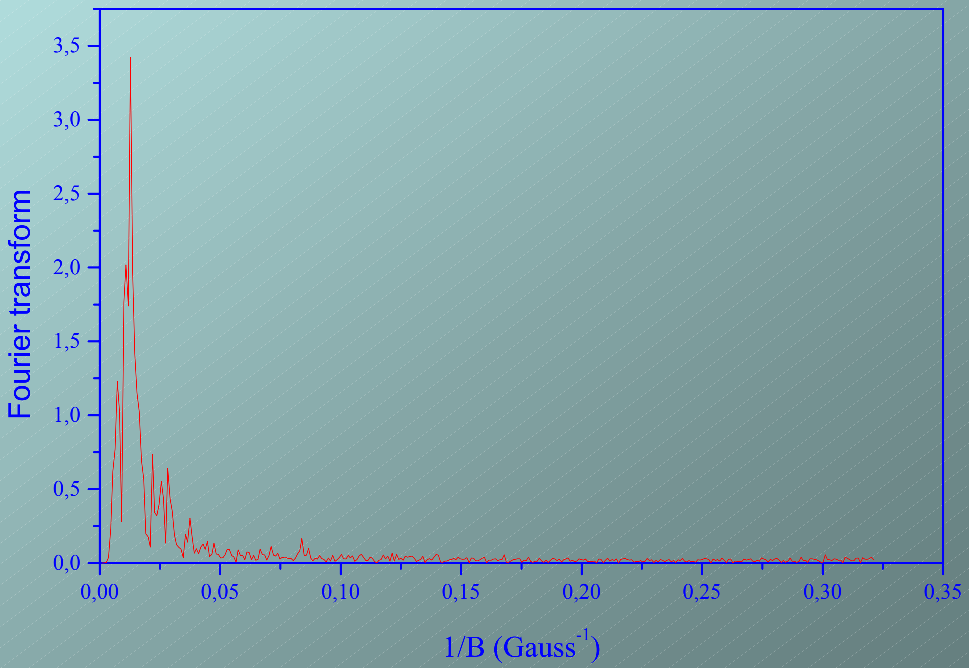
Clear h/e peak
Typical amplitude 0.02e^2/h

For a single cell one obtains a typical amplitude: 0.05 e^2/h

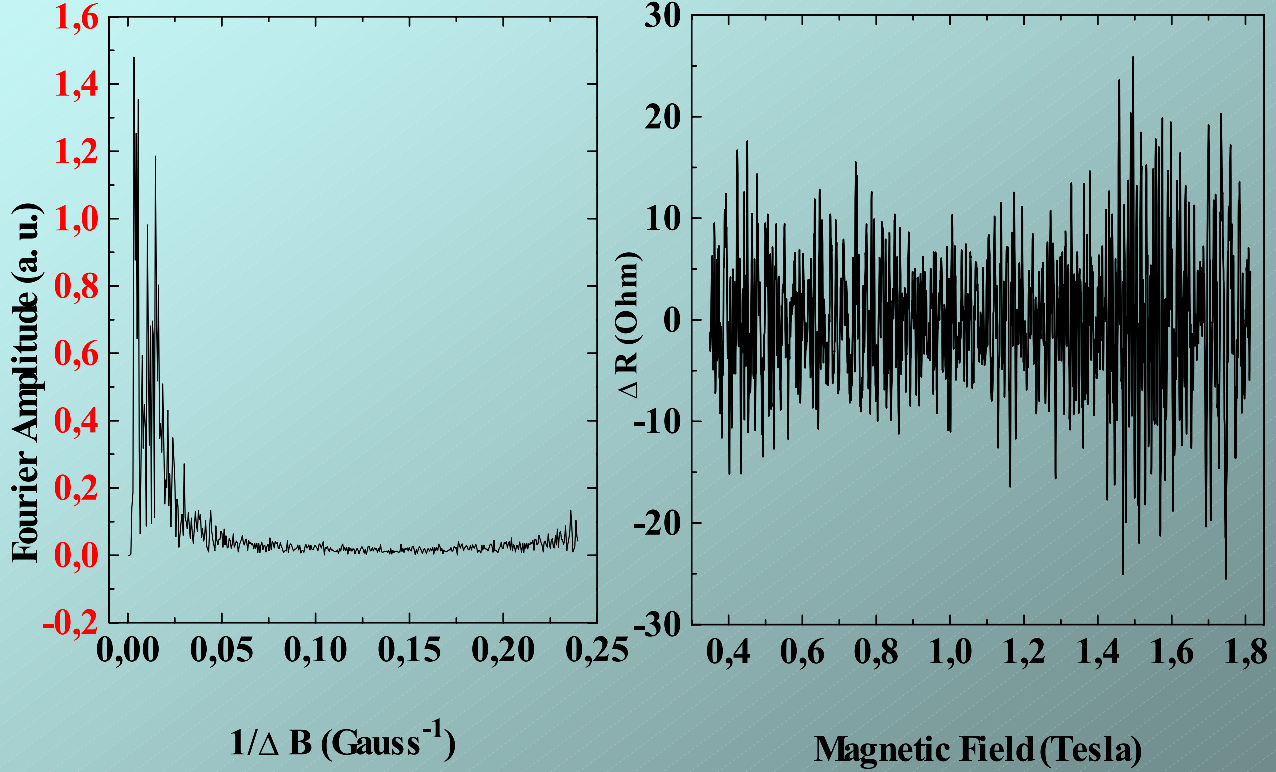
Expected amplitude with ensemble averaging:
$1/\sqrt{2500} \longrightarrow 0.001\ e^2/h$

other samples



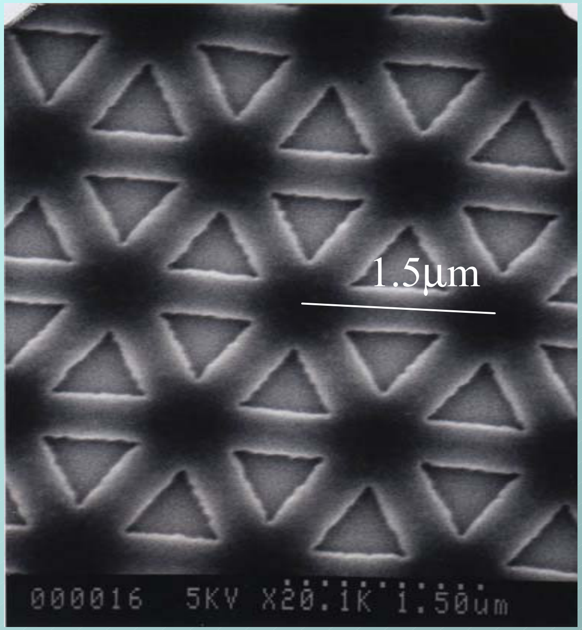


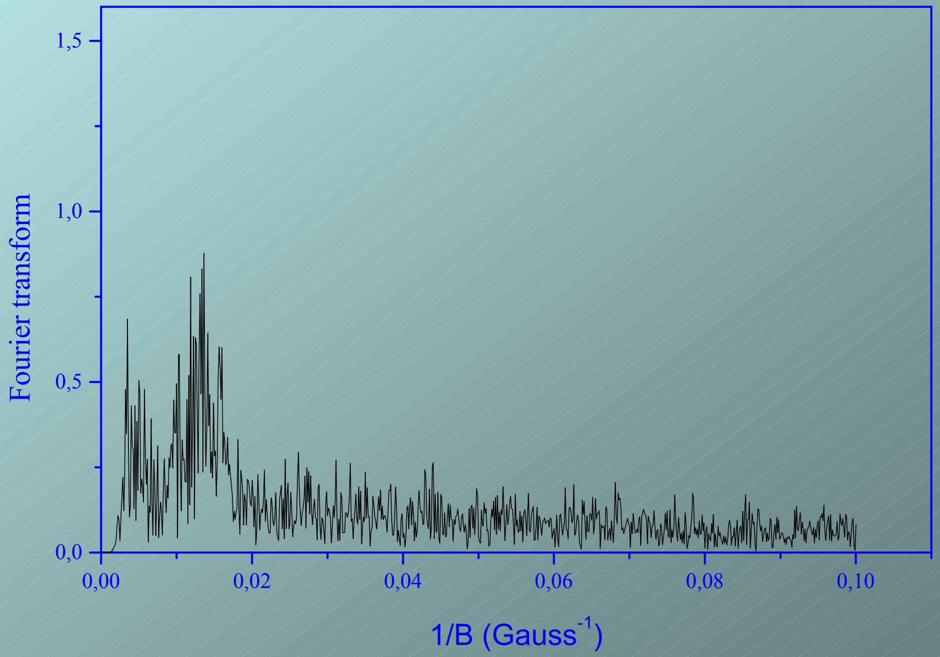
Magnetoresistance of the square lattice



For all measured samples the amplitude is always more than one order of magnitude smaller than the T3 one. This is of the order of the standard averaged value

Magnetoresistance of a triangle lattice





Characteristic lengths and temperature dependence

For an A-B ring when $L_{loop} = L_c > L_\Phi$ $\qquad \delta G_{h/e} \propto e^{-L_c/L_\Phi}$

As $L_\Phi \sim T^{-p}$ $\longrightarrow$ exponential decay of $\delta G_{h/e}$ with temperature

When $L_c < L_\Phi$ temperature averaging $\longrightarrow$ $\delta G \sim T^{-1/2}$

The change of regime occurs at $T=T^*$ such that $L_c = L_\Phi$

Temperature dependence of A-B oscillations

constant

Thermal averaging

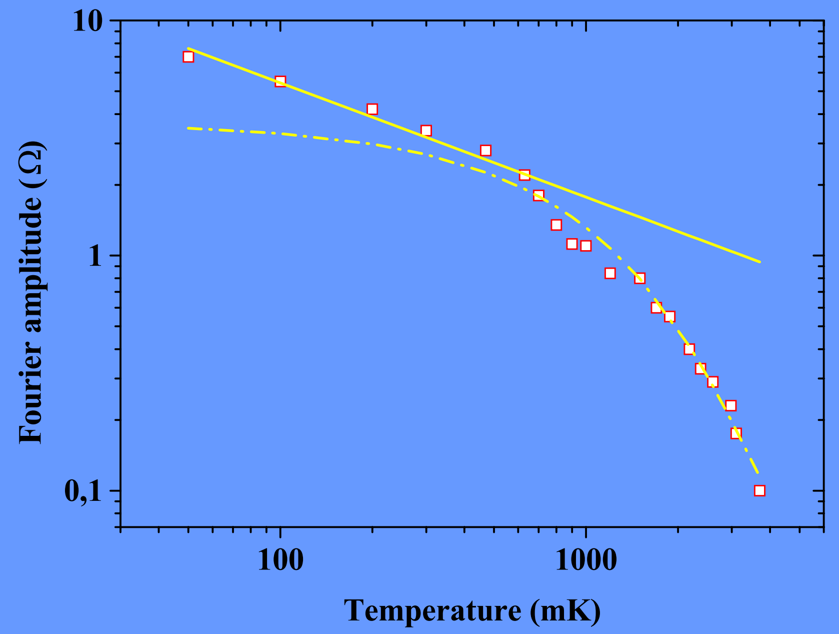
$\frac{E_{Th}}{k_B T} \Rightarrow \sqrt{\langle \Delta R_2 \rangle} \propto \sqrt{T}$

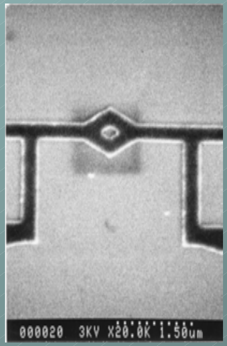
Exponental decay

T

$k_B T = E_{Th}$

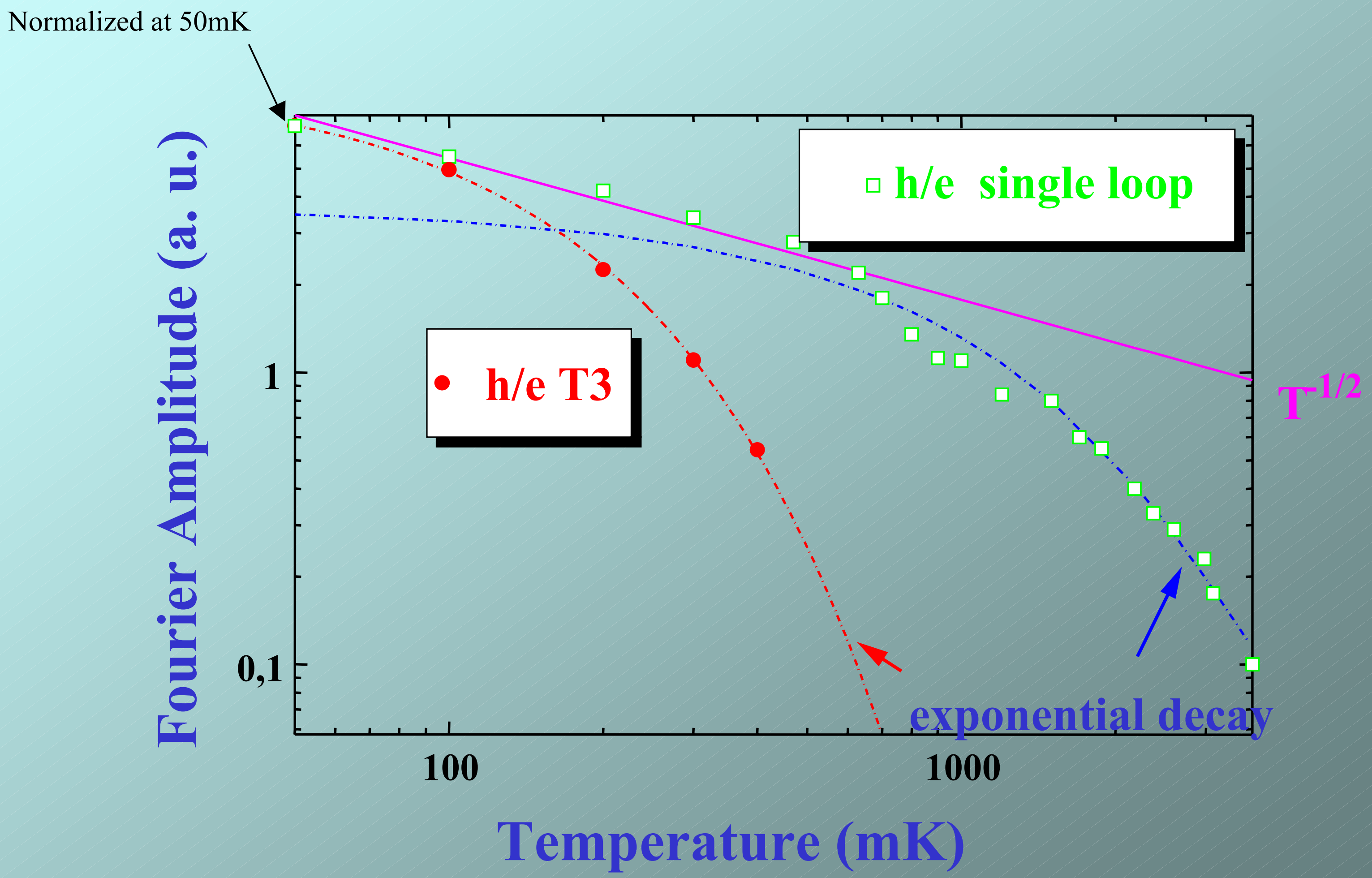
$L_\Phi(T) = L$





Single loop

Temperature dependence



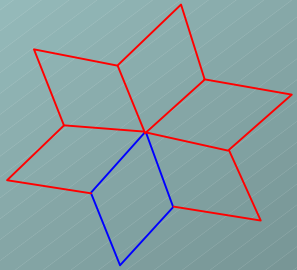
Temperature dependence results

$T^{*}_{T3} \sim 0.05K$ $T^{*}_{\text{single loop}} \sim 1K$

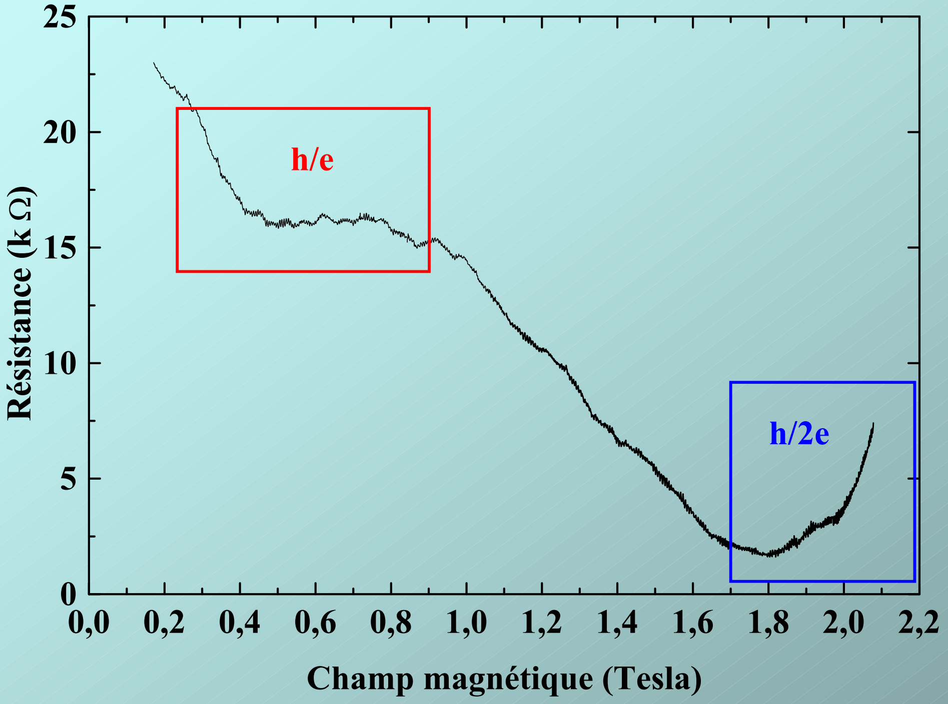
$\boxed{L_c^{T3} > L_c^{\text{ single loop}}}$

Using $L_\Phi \sim T^{-1/3}$ (1D e-e interaction)

$L_c^{T3} = 2.7\ L_c^{\text{single loop}}$ (lower value)



Magnetic field dependence of the oscillations



Doubling of the frequency at high magnetic field :

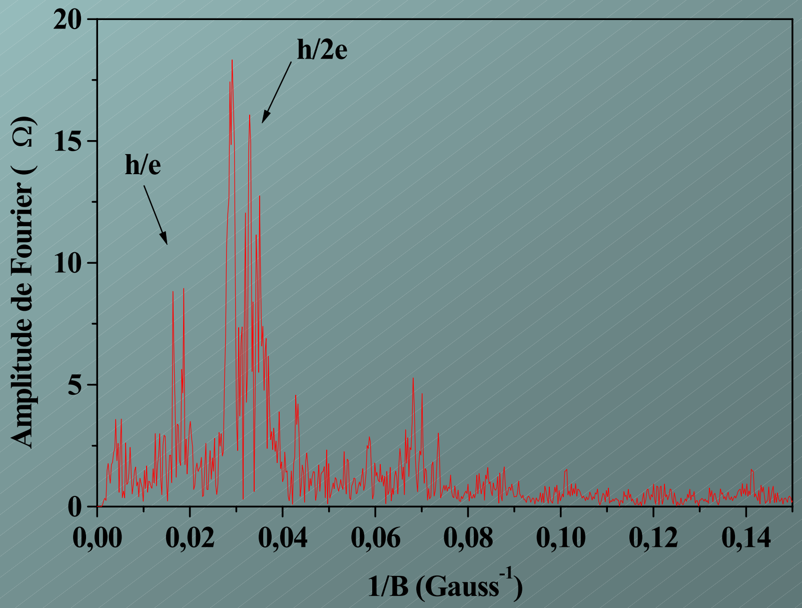
1)doubling of the flux

AAS, harmonique

2) doubling of the charge:

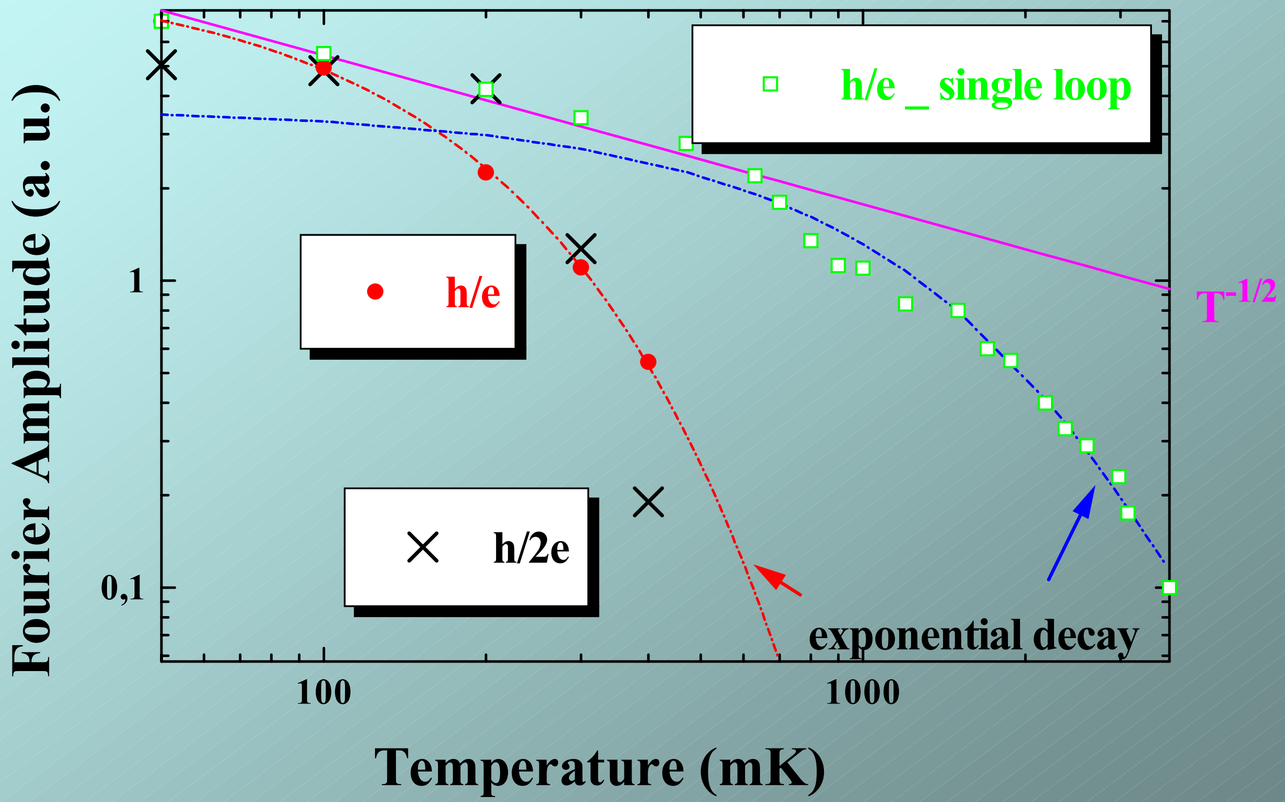
e-e interactions

J. Vidal, B. Douçot, R. Mosseri, P. Butaud,
Phys. Rev. Lett., 85, 3906 (2000)



R_{bond} <8kΩ , no Coulomb blockade effect is expected

Temperature dependence of h/2e oscillations

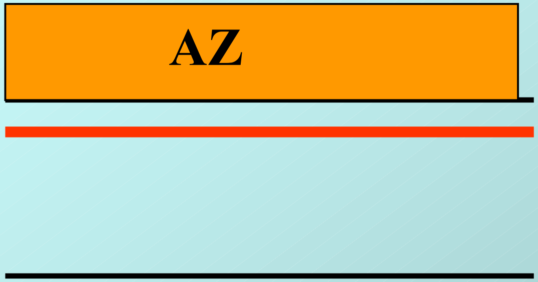


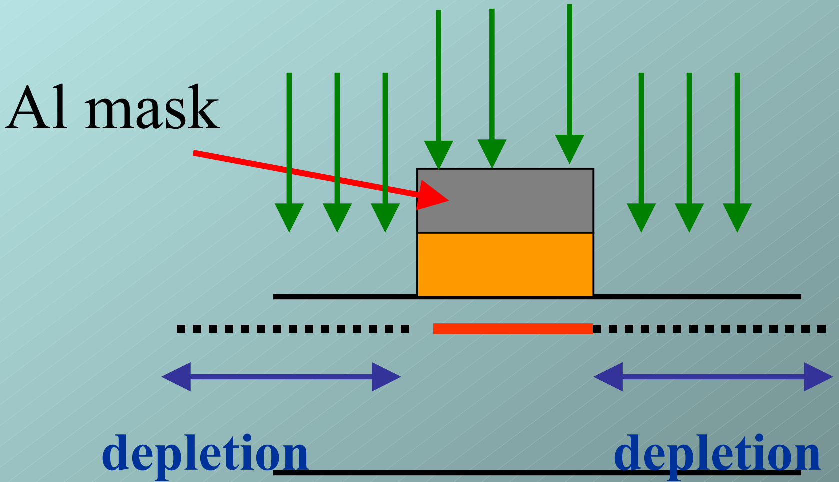
Same temperature dependence as h/e for the T3

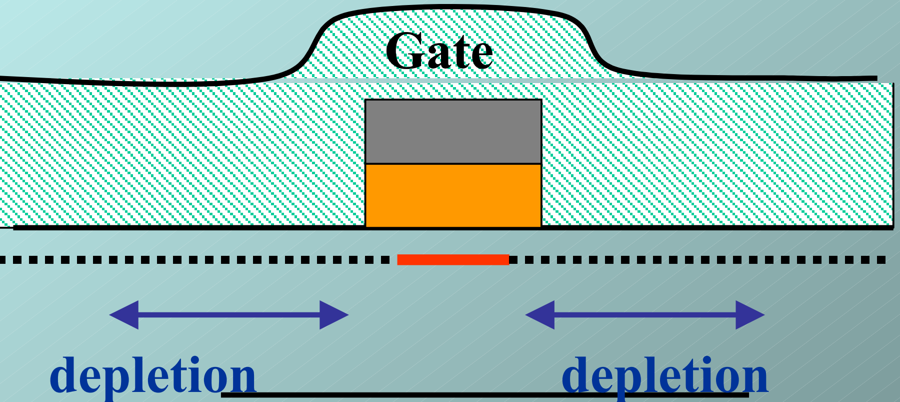
$\longrightarrow$ link to the cage

No such frequency doubling for single ring!

Samples with an electrostatic gate



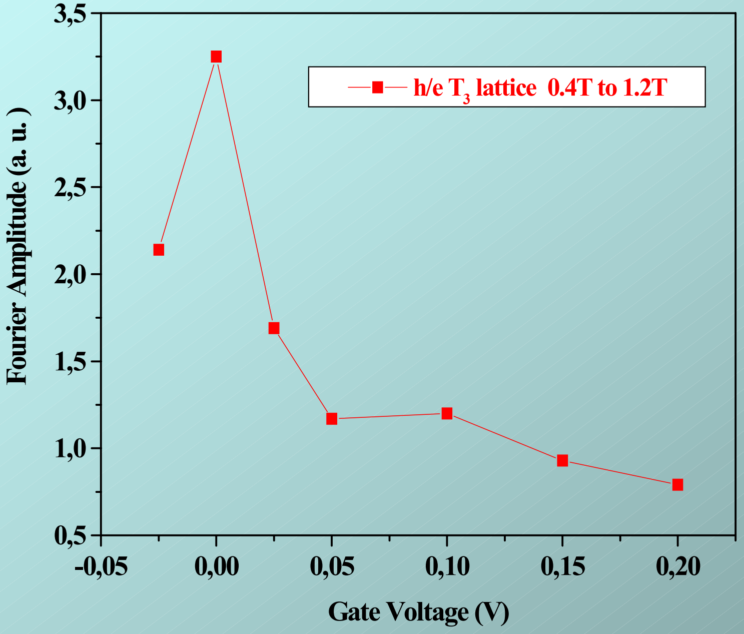




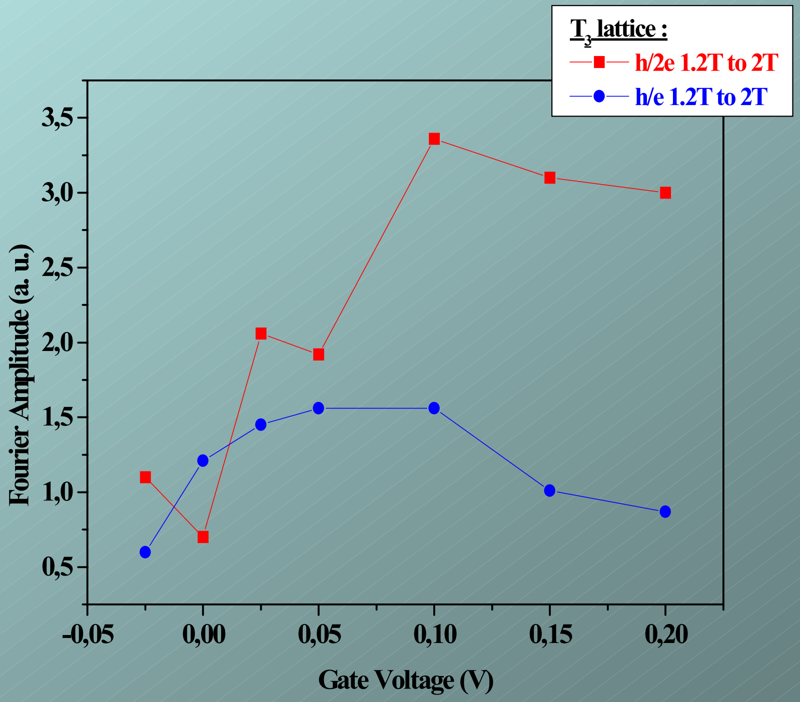
With an electrostatic gate :

1. channel number
2. electron density

Amplitude of the oscillations versus the channel number



h/e signal increases when N decreases



h/2e signal decreases when N decreases

These measurements confirm both the existence of the cage effect and of the frequency doubling

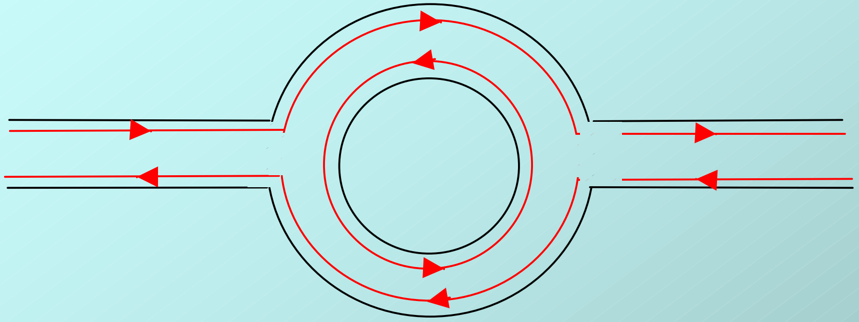
What is the nature of the h/2e signal?

AAS oscillations are usually destroyed by magnetic field because of aspect ratio → One-dimensional wire at high magnetic fields, but the width of the peak is not smaller, and temperature dependence indicates same size.

electron-electron interactions → Different behavior with electron density/channels number than low field oscillations

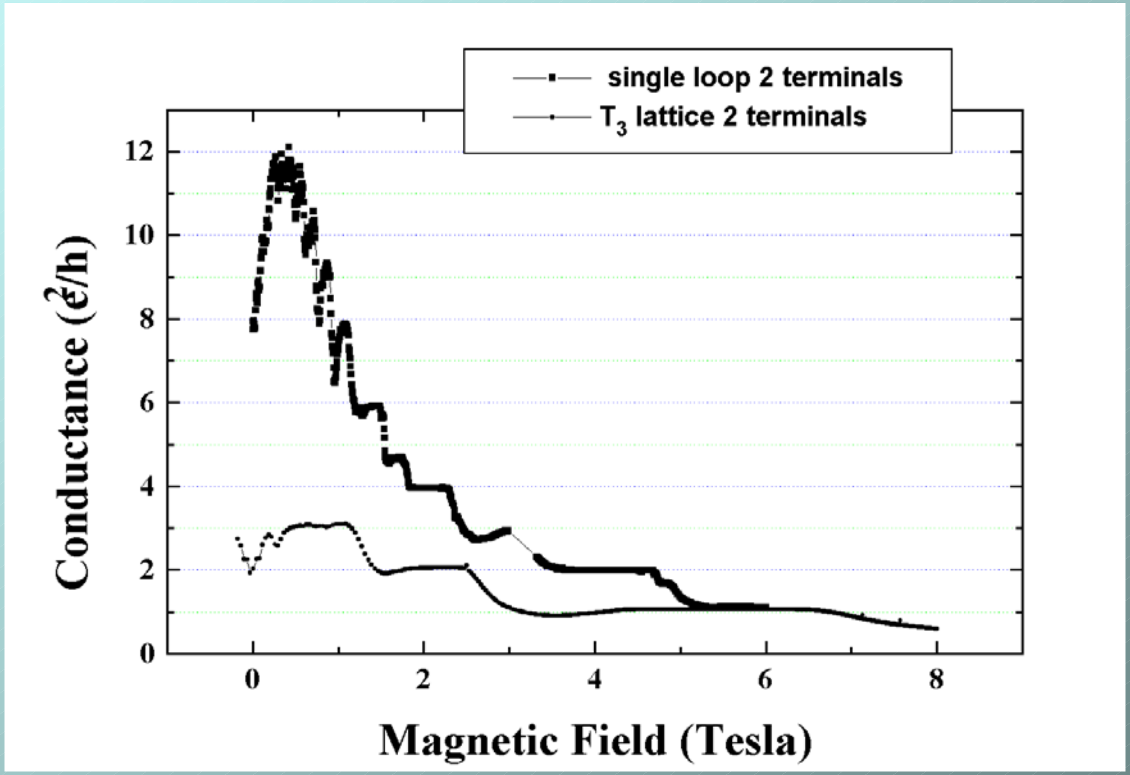
Landau level effect (C. Ford expt) → No h/2e for single ring
AB osc. disappear when LL developpe

Edge states in QH regime



Suppression of A-B effect

(Timp et al)

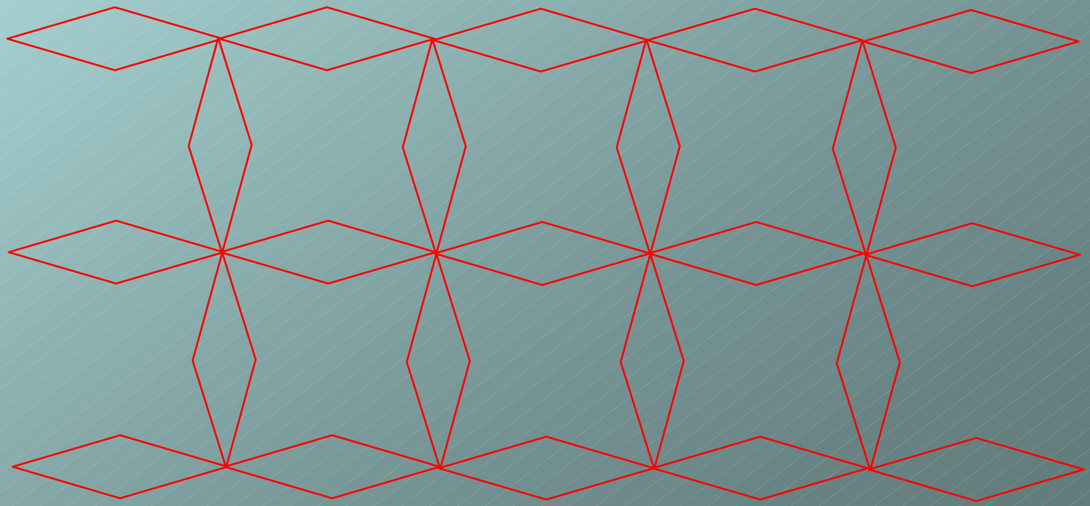


Needs to adjust the etching process in order to mixte edge states

(IBE 250V, time adjustment)

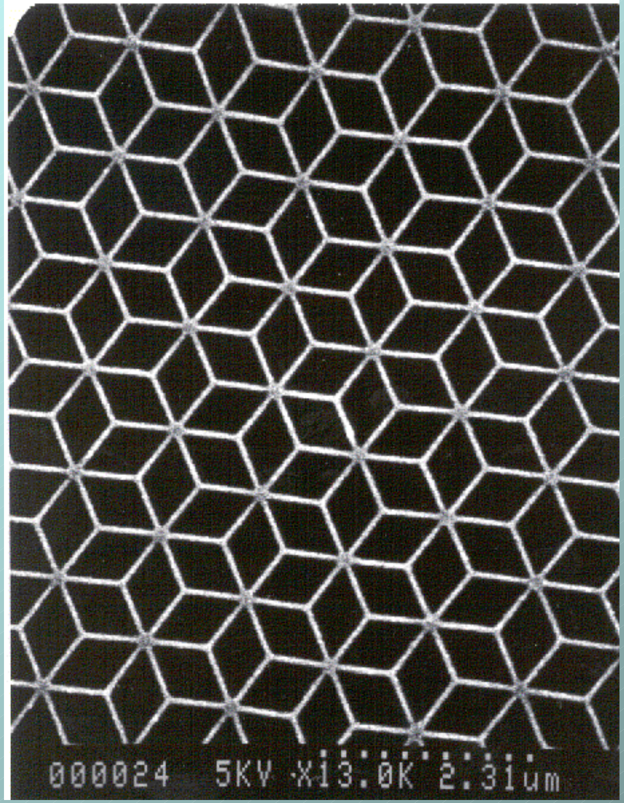
Need more experiments

- Change interaction strength: low density 2DEG
- Other geometries



More disordered systems: the metals

Effect of the disorder: Au, Cu and Ag samples



Two lattices have been fabricated:

- 0.7 μm length, 100G/Φ_0
- 0.4 μm length, 300G/Φ_0

No significant h/e signal has been detected

(CRTBT 10^{-5} $\delta R/R$ resolution)

sensitivity of the cage effect to disorder

Conclusions

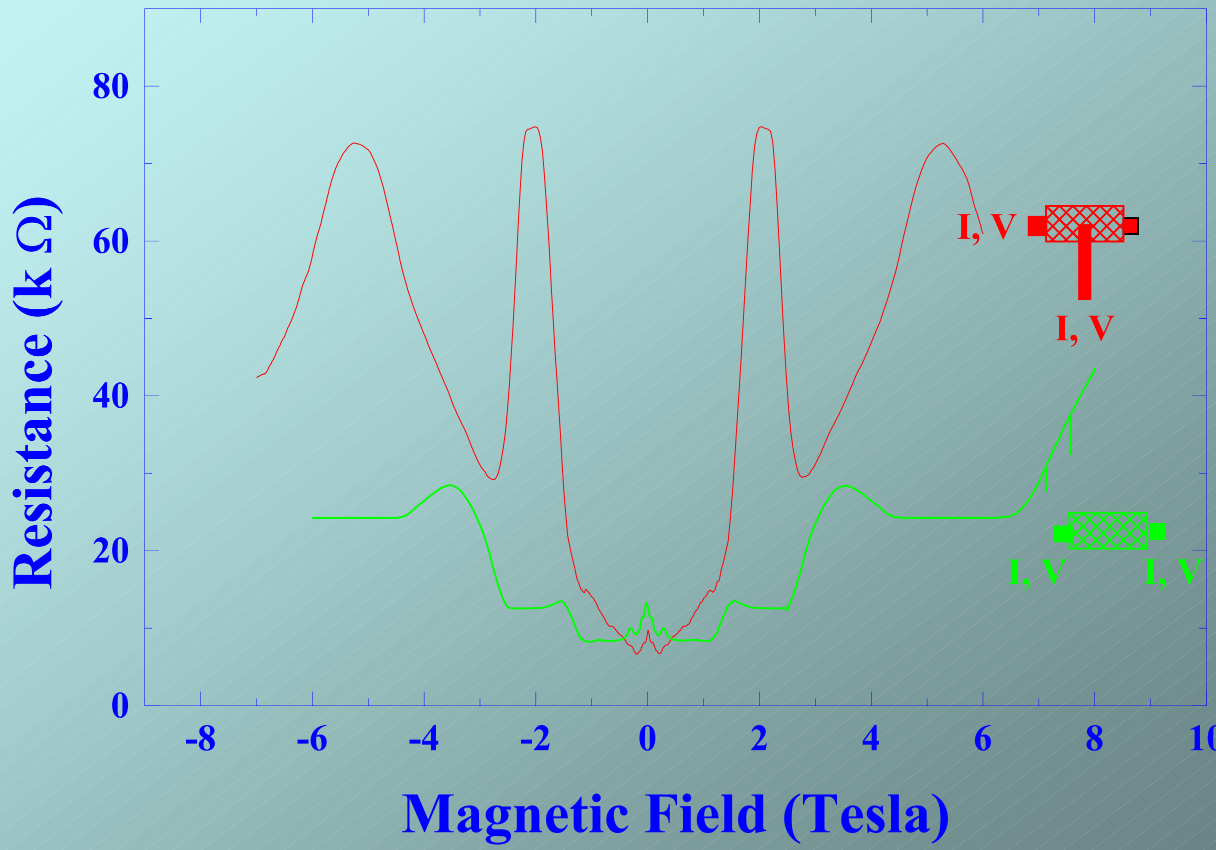
- First observation of h/e oscillations in a 2D lattice
- Agreement with theoretical predictions for the T3 lattice amplitude compared to the square lattice
- Temperature dependence confirms the role of the cages
- No oscillations in metal samples: role of disorder
- Unexpected frequency doubling at high magnetic fields
  - same T dependence : linked to cage
  - no signal for single ring
  - different behavior with chanel number compared to low field regime
  - electron-electron interactions ?

New interests for lattices with exotic topology in high mobility systems

Use of low density 2DEG to check the role of interactions

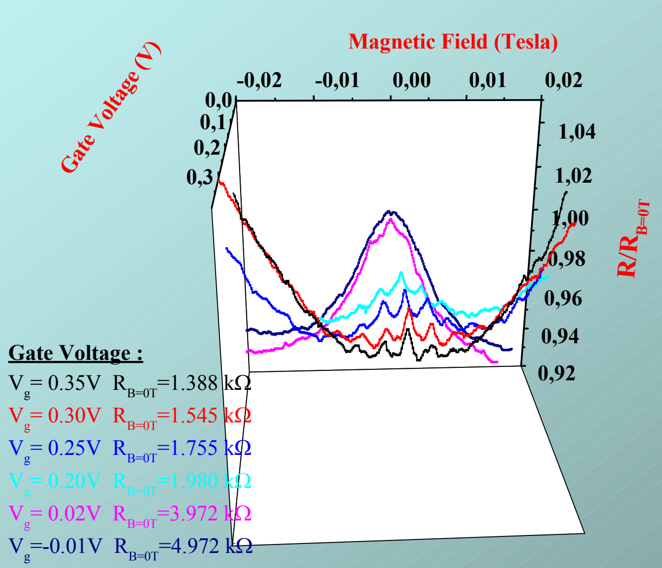
Other topologies

Evidence of edges states on the whole lattice

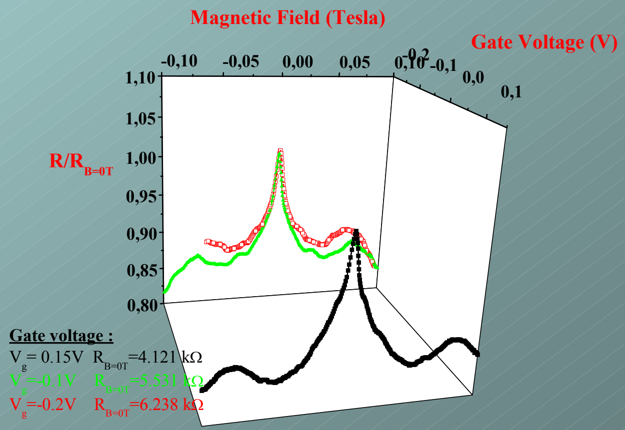


AAS OSCILLATIONS

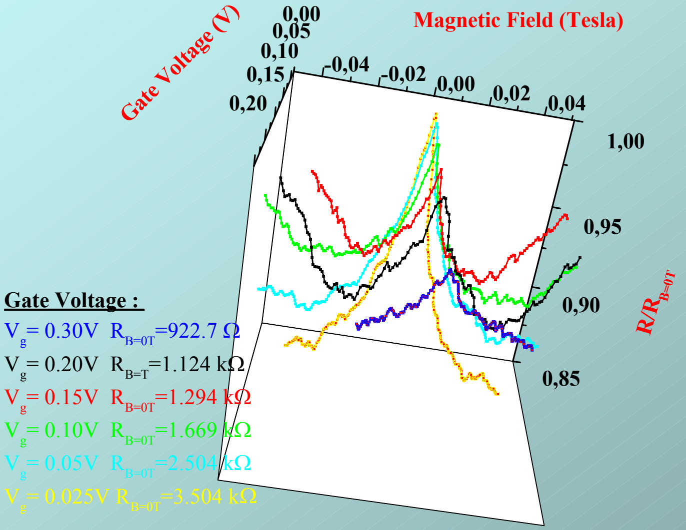
Square Lattice :



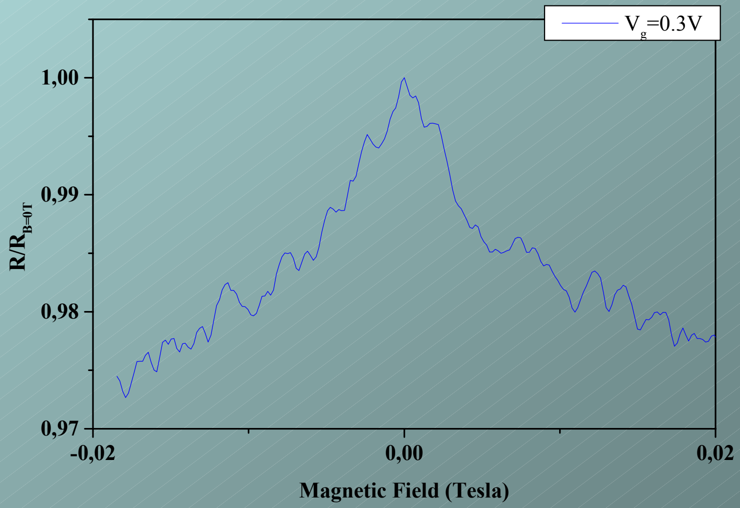
Triangular lattice :



T_3 lattice :



Gate Voltage (V)
0,00
0,05
0,10
0,15
0,20
Magnetic Field (Tesla)
-0,04
-0,02
0,00
0,02
0,04
1,00
0,95
0,90
0,85
R/R_B=0T
Gate Voltage :
V_g = 0.30V R_B=0T=922.7 Ω
V_g = 0.20V R_B=T=1.124 kΩ
V_g = 0.15V R_B=0T=1.294 kΩ
V_g = 0.10V R_B=0T=1.669 kΩ
V_g = 0.05V R_B=0T=2.504 kΩ
V_g = 0.025V R_B=0T=3.504 kΩ



V_g=0.3V
1,00
0,99
0,98
0,97
R/R_B=0T
-0,02
0,00
0,02
Magnetic Field (Tesla)

QHE in the Square lattice :