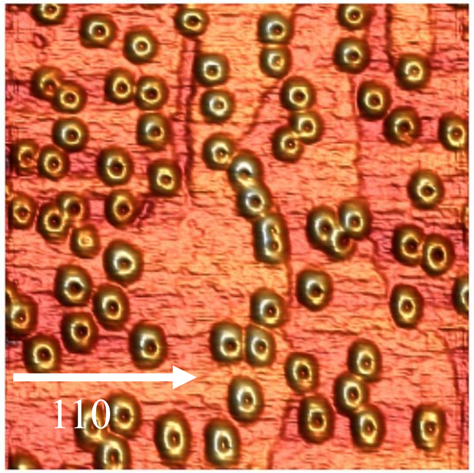
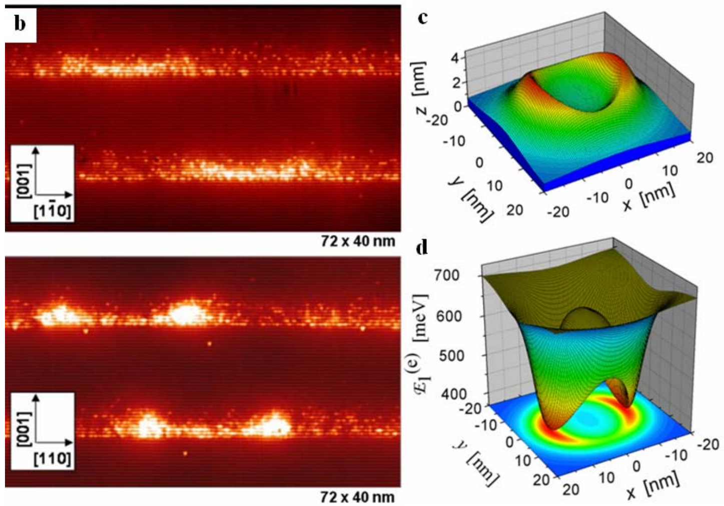
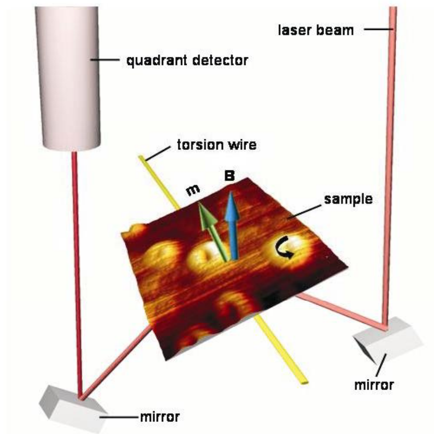
Self Assembled Quantum Rings







Dr. Jorge M. García

*MBE LAB, Instituto de Microelectrónica de Madrid ,CNM (*CSIC*), C/Isaac Newton 8, PTM, 28760 Tres Cantos (Madrid),Spain*

Present address: Bell Labs, Mountain Avenue, 600-700, Murray Hill, New Jersey, USA

1889 1900 1921 1939 1964

1969 1995

AT&T Bell Laboratories

Lucent Technologies
Bell Labs Innovations

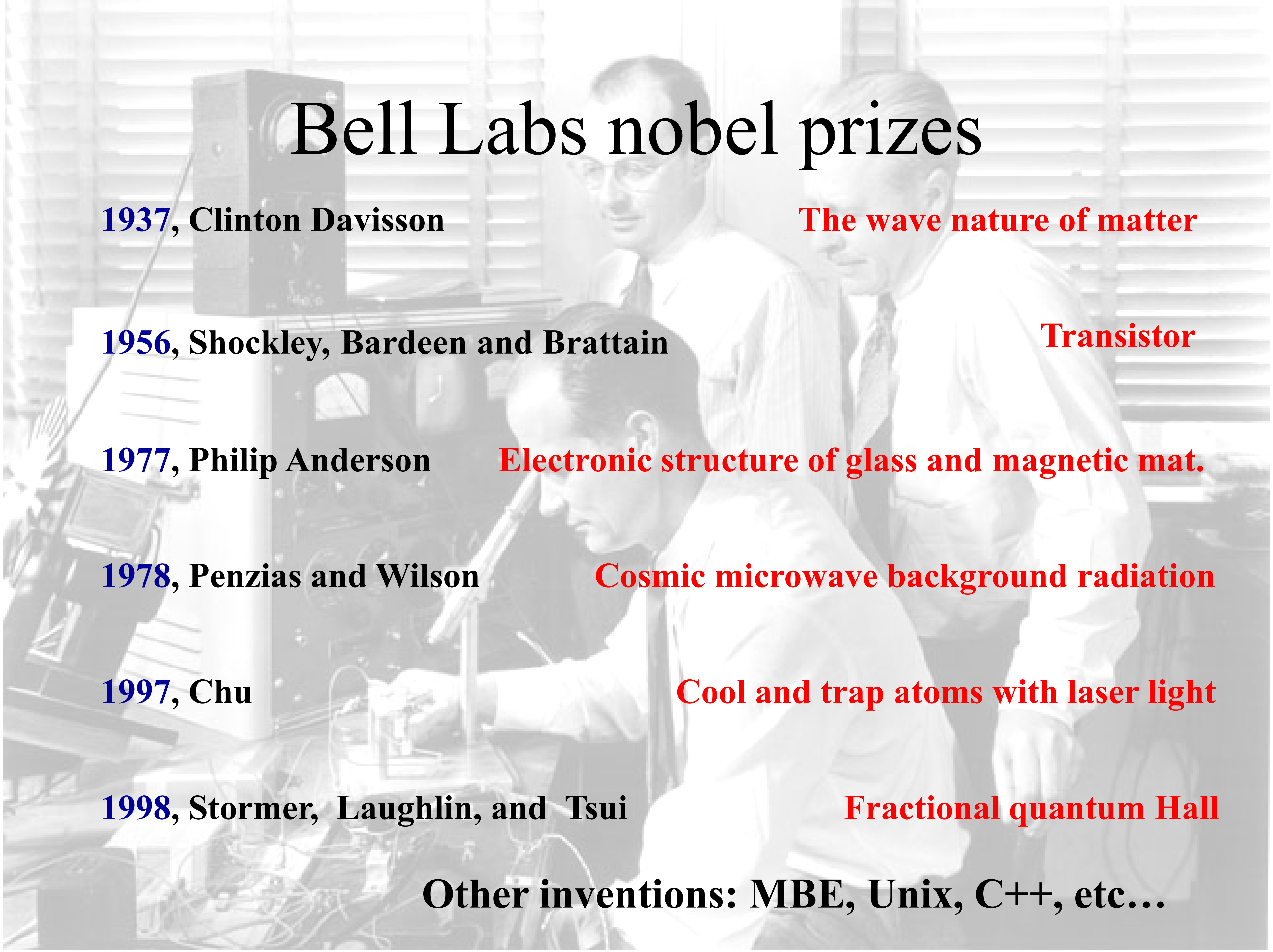
ALCATEL → Alcatel-Lucent ← Lucent Technologies Bell Labs Innovations

2006

60 years of basic research,
6 nobel prizes

"Bell Labs bottoms out" (Institute pulls plug on basic research)

20 August 2008 | *Nature* 454, 927 (2008)



Bell Labs nobel prizes

1937, Clinton Davisson	**The wave nature of matter**
1956, Shockley, Bardeen and Brattain	**Transistor**
1977, Philip Anderson	**Electronic structure of glass and magnetic mat.**
1978, Penzias and Wilson	**Cosmic microwave background radiation**
1997, Chu	**Cool and trap atoms with laser light**
1998, Stormer, Laughlin, and Tsui	**Fractional quantum Hall**

Other inventions: MBE, Unix, C++, etc…

Self Assembled Quantum Rings
Outline

- Intro...
- Growth of Self assembled Quantum Ring
- Structural Properties: XTEM & XSTM
- Optical properties: PL
- Magnetic Fields
  - Magneto-torsion
  - PL
- Conclusions

History of self assembled Rings

- InAs/GaAs
  - QR at UCSB (study of QD in RTD)
    - J.M. Garcia et al. APL, 71 (1997) 2014
  - QR at IMM (fundamental growth studies)
    - D.Granados et al APL, 82 (2003) 2401
- InAs/InP
    - T. Raz et al. APL 82 (2003) 1706, …
- SiGe
  - J.Cui, APL, 83 (2003) 2907, …
- Droplet epitaxy growth
  - S. HUANG et al, Solid state data. B, vol. 121-23 (2007), 541, ...

Motivation

- Quantum information manipulation

  A Quantum Dot Single-Photon Turnstile Device,

  P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, Lidong Zhang,E. Hu, A. Imamogùlu,

  SCIENCE **290,** p 2282 (2000)

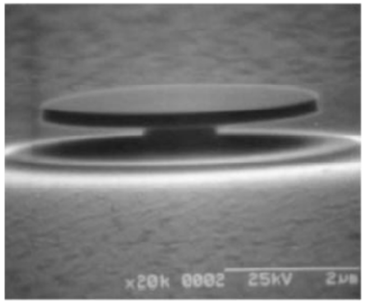
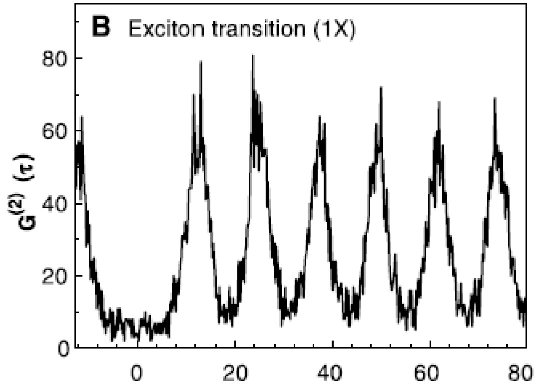


Fig. 1. The microdisk structure, which consists of a 5-µm-diameter disk and a 0.5-µm post. The GaAs disk area that supports high-quality factor WGMs is 200 nm thick and contains InAs quantum dots.



- Flexibility of design required for devices with nanostructures in the active region.
  - Lasers, solid state near RT Q-bits operation, etc…

- Non trivial quantum geometry. Rings under Magnetic Field

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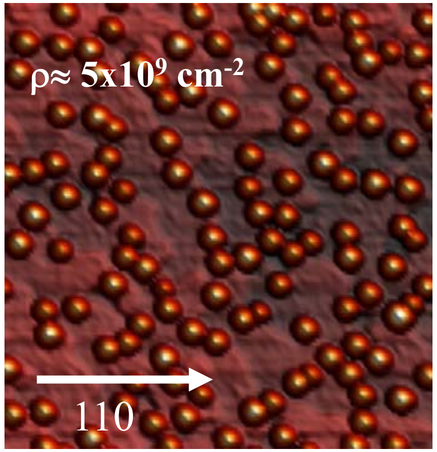
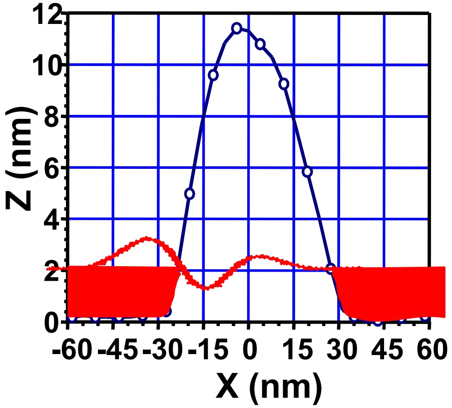
GROWTH - From Dots to Rings: In(Ga)As/GaAs(001)

Quantum Dots



AFM 1x1 micron^2



T_{QD}=540ºC,

2 ML InAs

Partial cap

2 nm GaAs

+

anneal

SIZE of capped QD

From X-TEM and X-STM

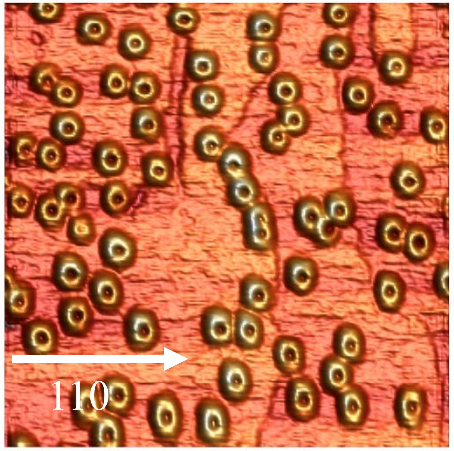
H ~6nm

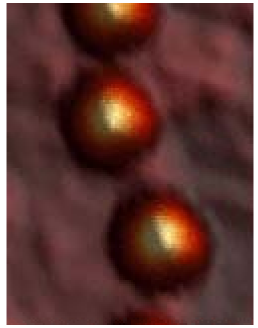
D ~30nm

20% GaAs

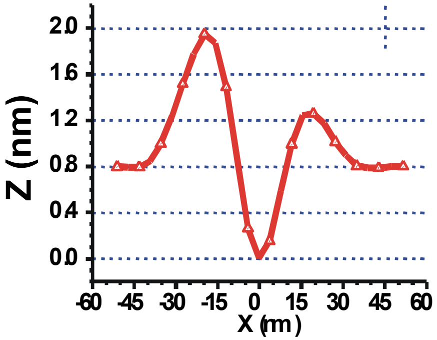
Large Ga-In mixing

QR In(Ga)/AsGaAs (001)





AFM 1x1 micron^2



SIZE of capped QR

X-TEM and X-STM

H ~3.5 nm

D ~20nm along [1-10],

~25nm along [110]

Vertical size reduction

Requierements for Ring formation

- QD
  - Very uniform size distribution
  - Large QD. Height > 10 nm
  - (3.5×10^{-6} mbar As_2, Ts=540ºC)
- Ring formation
  - GaAs Capping with 20% height QD
  - Lower T (500ºC) and As_2

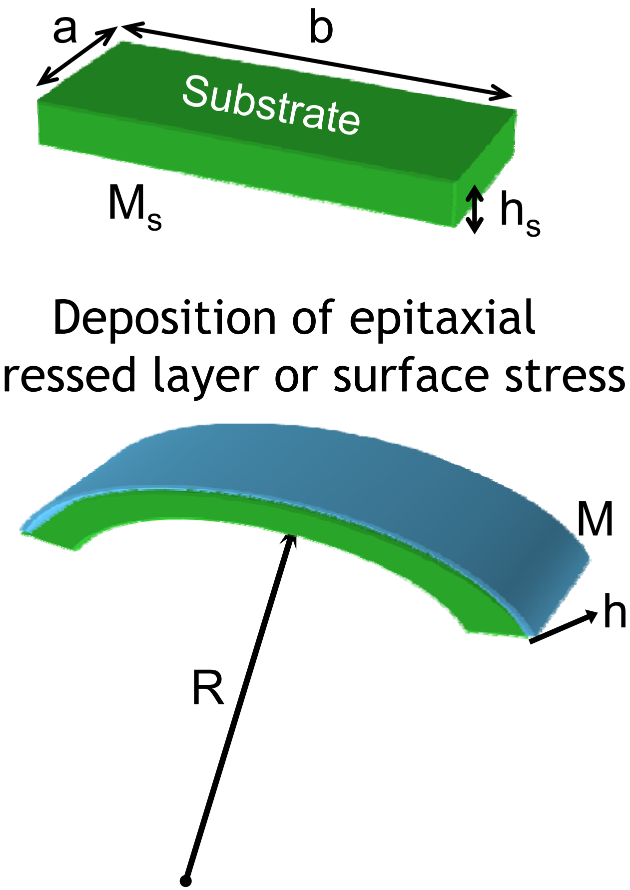
APPLIED PHYSICS LETTERS VOLUME 82, NUMBER 15 14 APRIL 2003

In(Ga)As self-assembled quantum ring formation by molecular beam epitaxy

Daniel Granados and Jorge M García[a)]

in situ, reak time Characterization

Morphology and relaxation processes during MBE epitaxial growth



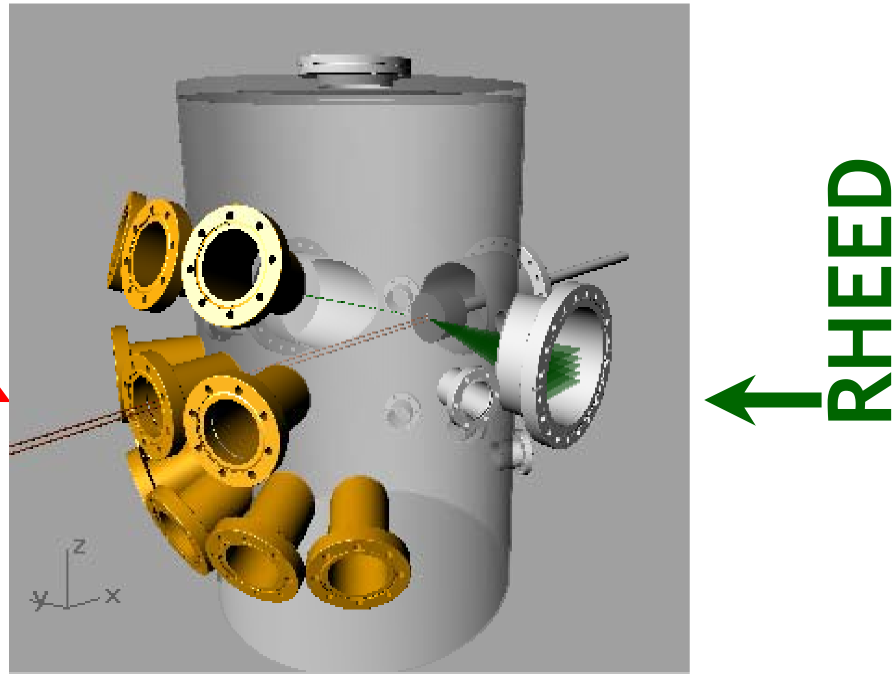
$\Delta\,(1/R) \propto \Delta\,$(surface tension)

$[\,\Delta\,(1/R) = 6\,\Delta\,(\sigma\, h)\,/\,(M_s\, h_s^2)\,]$

SPECIAL TECHNICS @ IMM

- Reflectance Difference (**RD**)
- **ACCUMULATED STRESS**

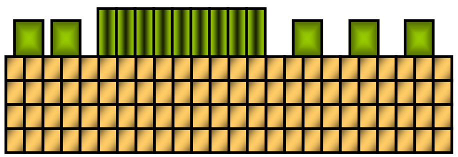
(monitoring of sample curvature measuring the deflection of two laser beam)



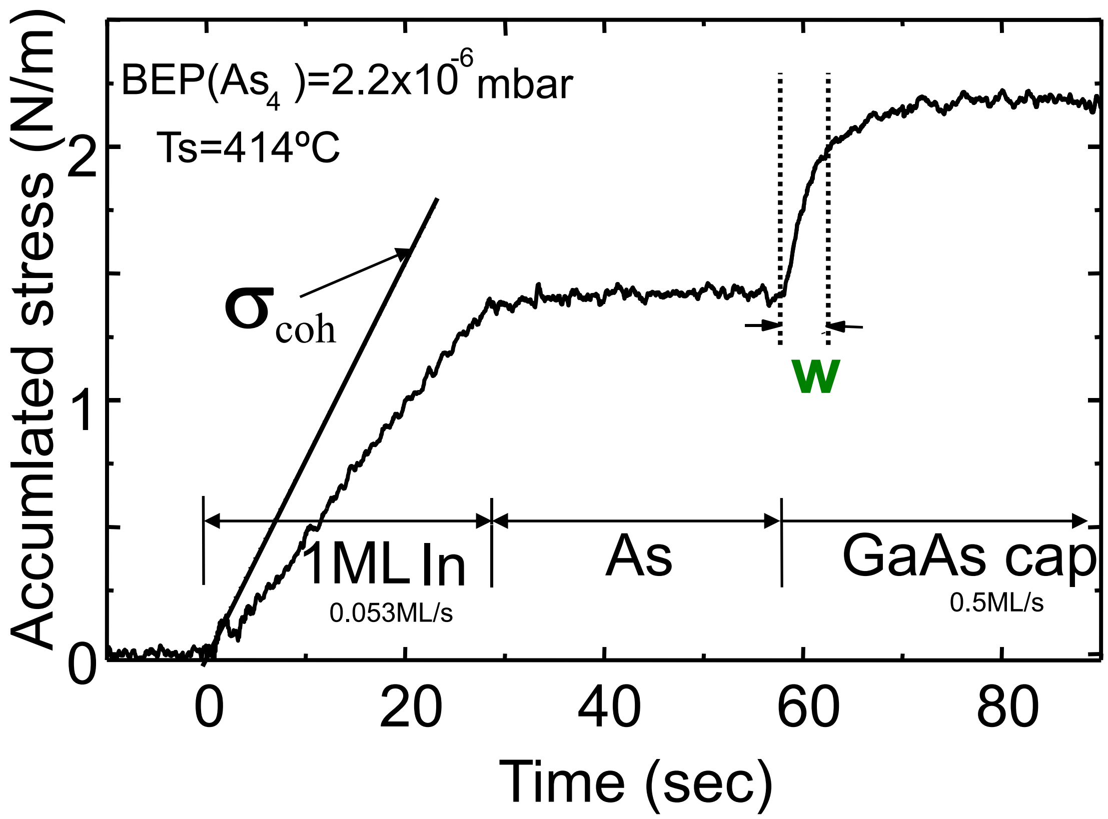
1ML InAs/GaAs(001)

Observed features

- Isotropic effect, [110] and [1$\bar{1}$0]
- Linear incorporation rate<σ_{coh}
  $\sigma_{coh}=M_f\cdot(a_f-a_s)/a_f \approx 2$ N/(m·ML)
- No sharp interface, In segregation lengh **W(T)**
- Unexpected increase of Stress Thickness while capping "pseudomorphic" InAs



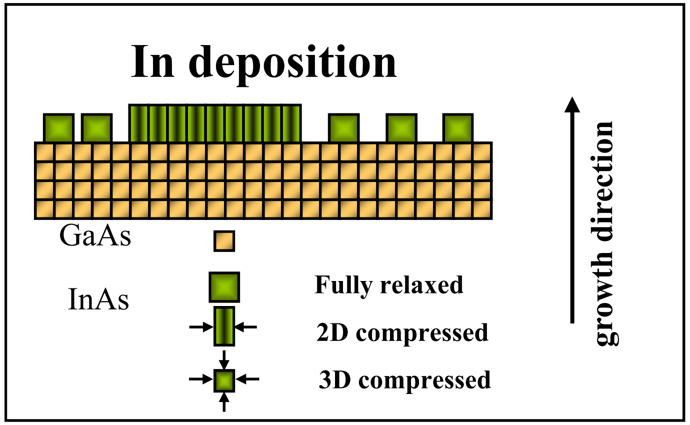
1ML InAs/GaAs(001) + GaAs CAP

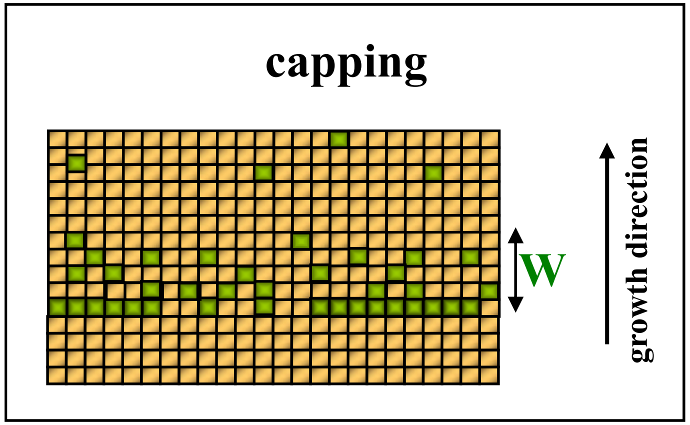


J.M. García et al. APL 77, 409 (2000)
J.P. Silveira et al, J. Cryst. Growth, 227-228, 995, (2001)

Wetting Layer vs. Embedding Layer

Liquid “Floating” Indium

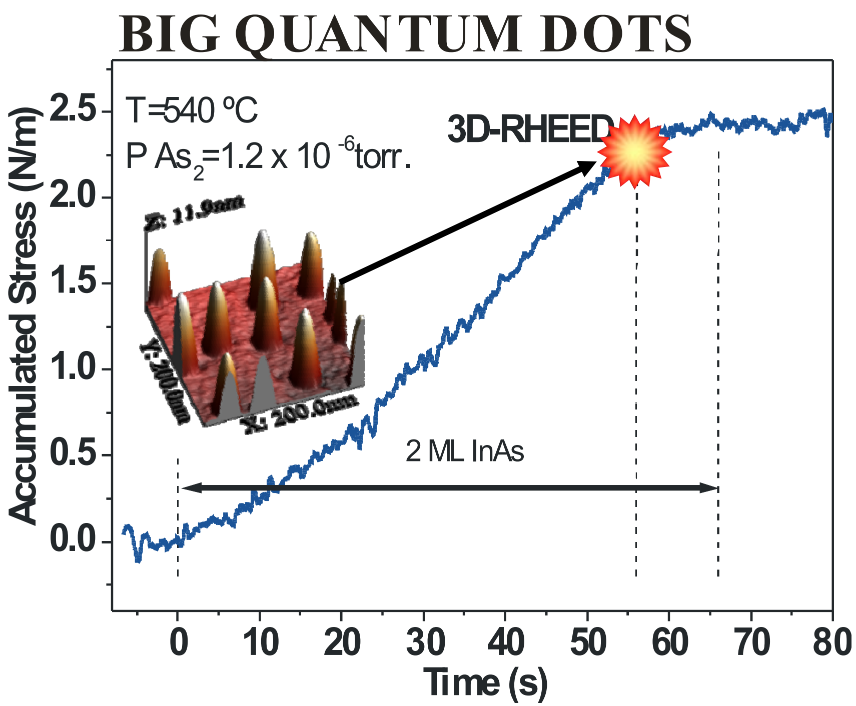


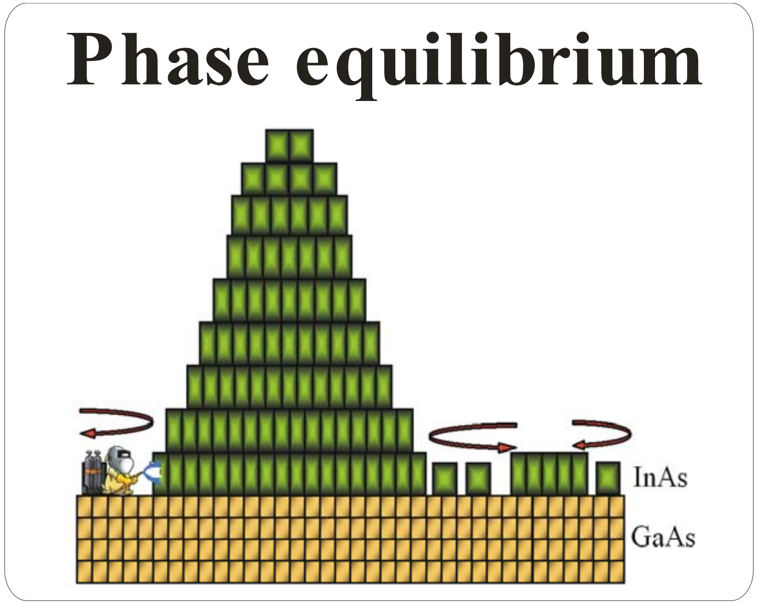


InAs(solid) + In (liquid) + InAs(liquid)

Dinamical equilibrium in which the stress elastic energy plays the main role

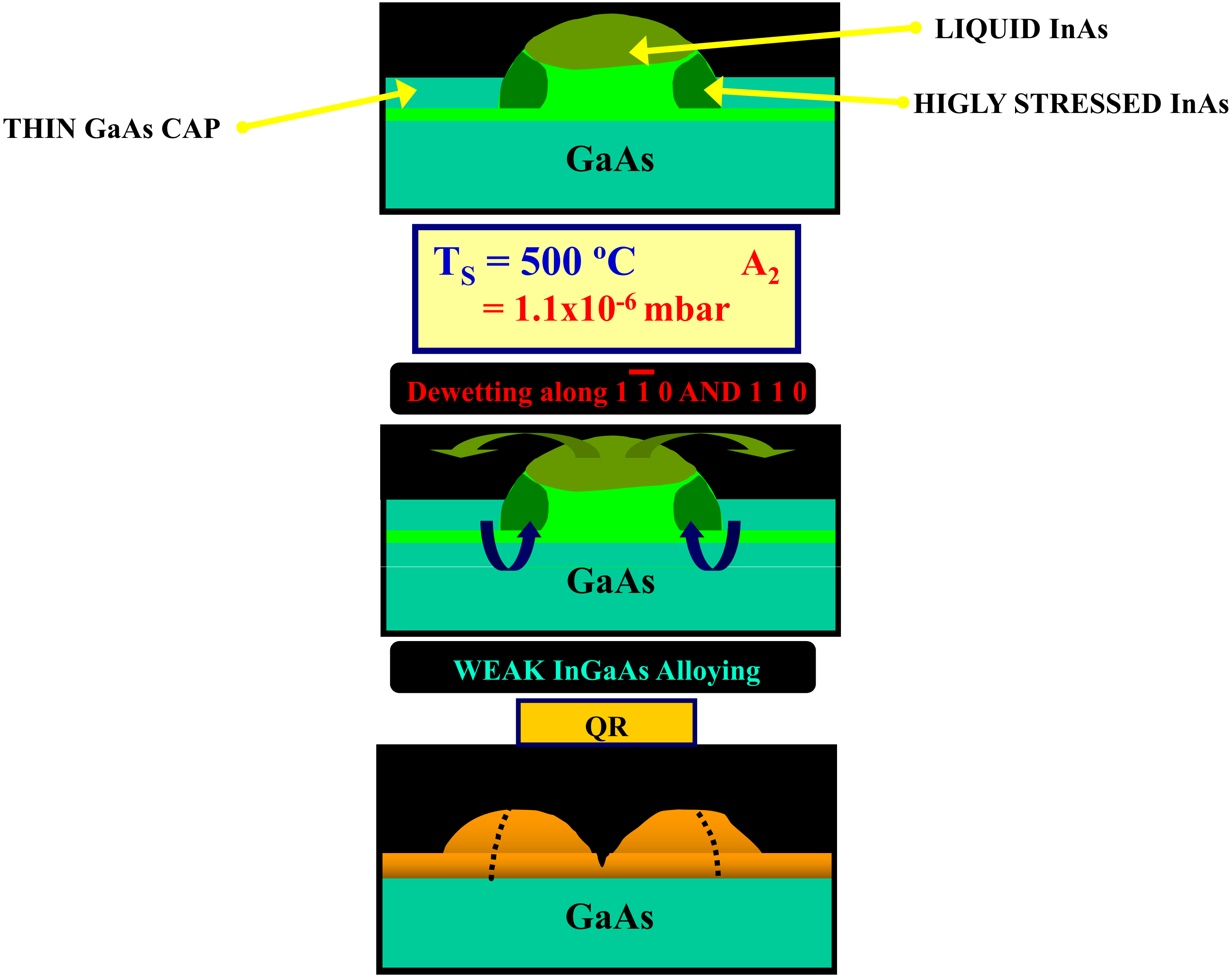
Accumulated Stress (AS) during Dots formation





- **Relaxation of incoming material on top of QD**

TRANSFORMATION SCHEME



Accumulated stress
Partial sumary

- Large fraction of In is in a liquid-like, stress-free state, which “floats” and progressively incorporates into the capping layers.
- Stress induced melting of QD tip during capping → Enhancement of mobility → nanoeruption

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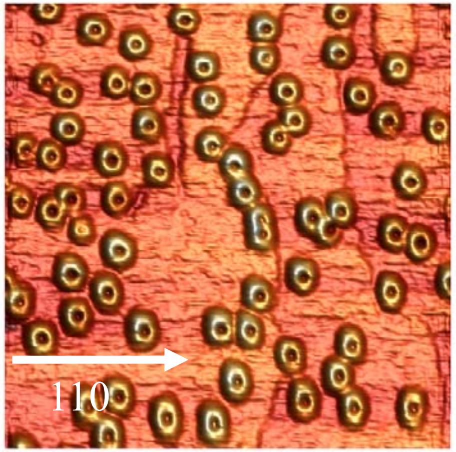
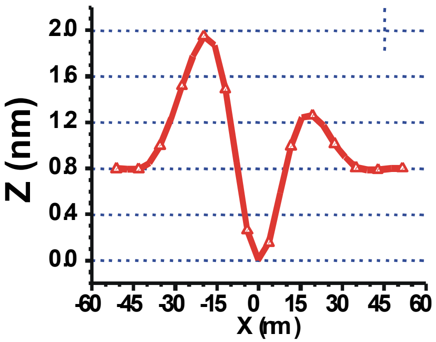
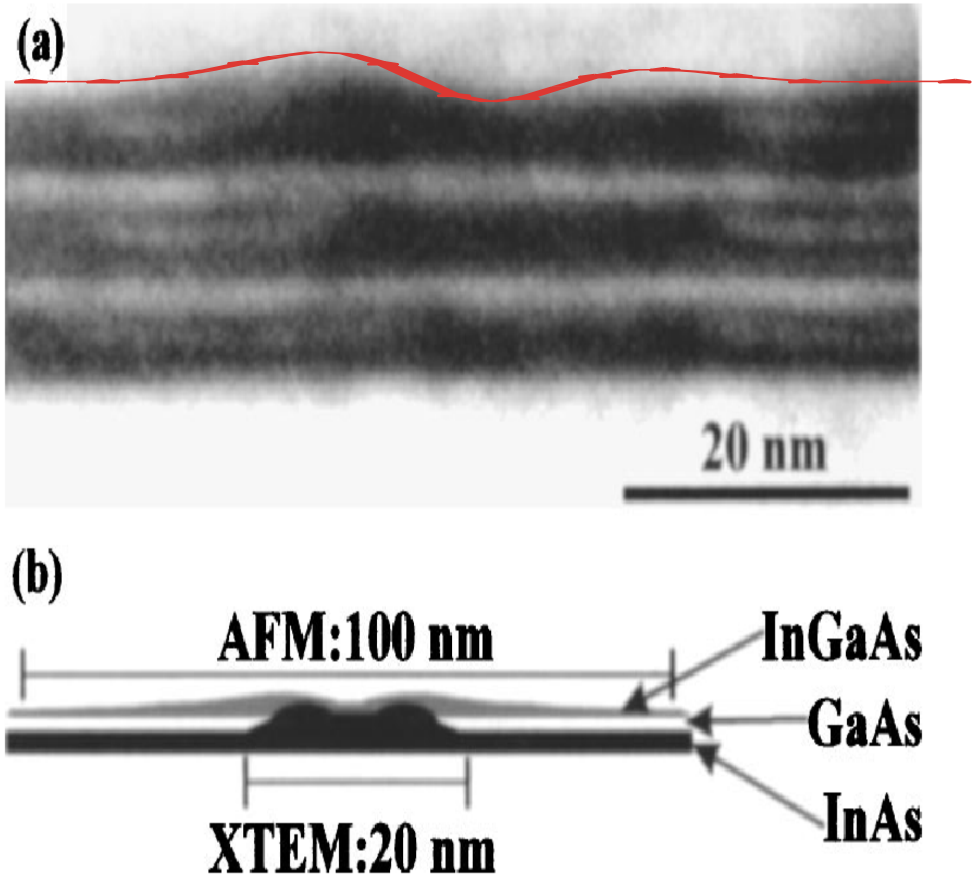
Ring Shape is preserved after capping



AFM 1x1 micron^2



AFM profile



Daniel Granados et al.APL. 82, 2401 (2003), APL 86, 071918 (2005)

X-STM of capped Rings

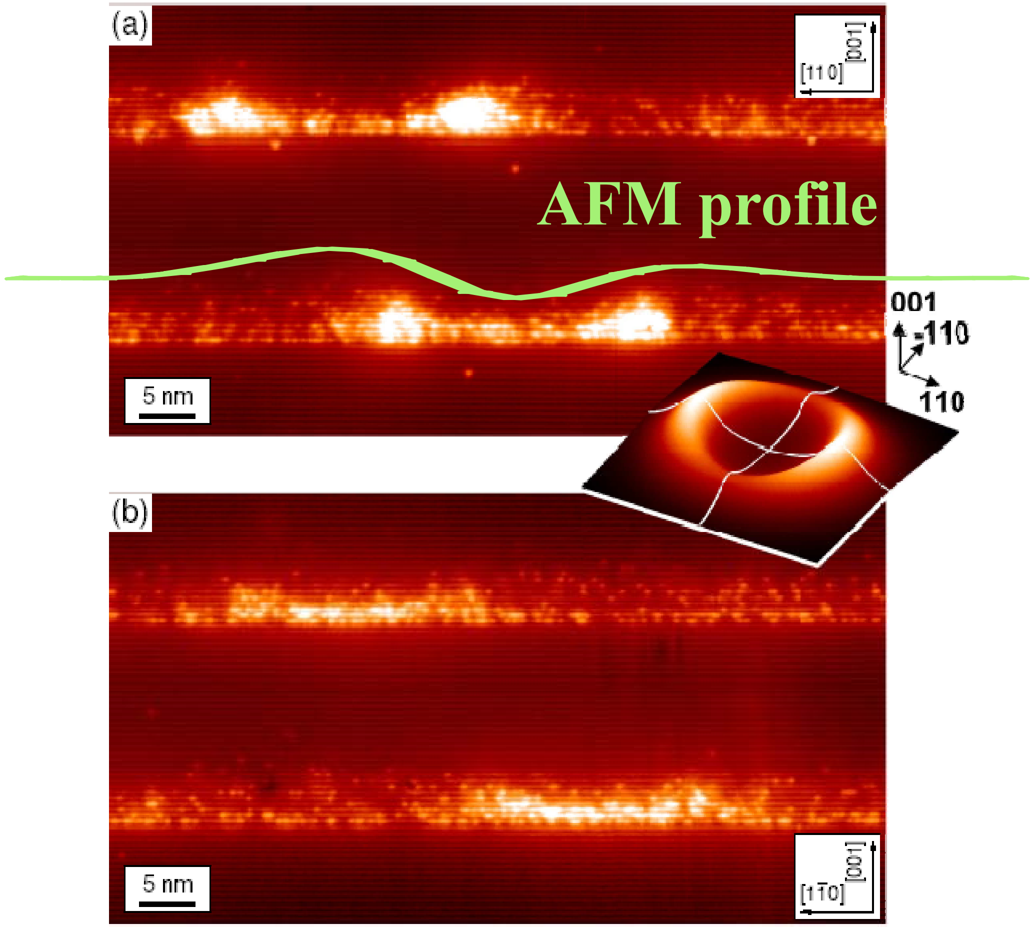


Figure 2.6: Filled state X-STM image of a self-assembled InAs quantum rings cleaved in the (110)-plane (a) and in the (110) plane (b) showing the asymmetry of the rings on this sample. The inset shows the 3D model of the rings observed by X-STM. Image from [13].

Dr. Paul Koenraad, Univ. Eindhoven

P. Offermans et al. Appl. Phys. Lett. 87, 1 (2005)

Parametrization of potential from X-STM data

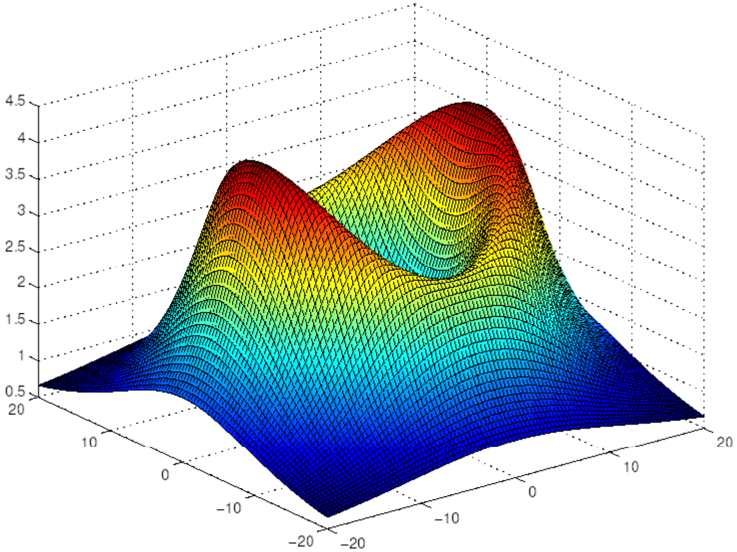


Figure 2.12: The shape of the ring as modelled by equations 2.22 and 2.23, with R=11.5nm, h_0=1.6nm, h_M=3.6nm, h_∞=0.4nm, γ_0=3nm and γ_∞=5nm. The anisotropy parameter ξ is set on 0.2

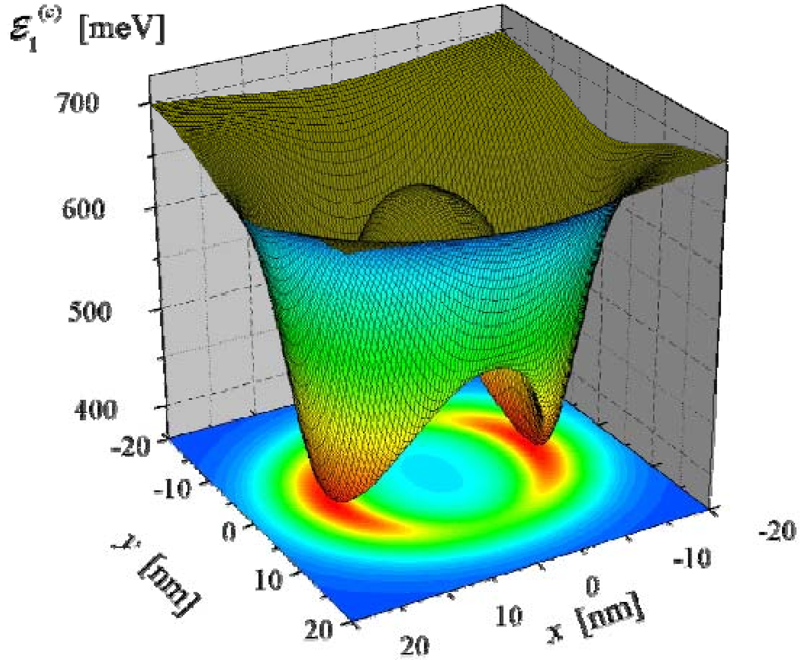


Figure 2.14: The adiabatic potential of a quantum ring with the same parameters as in figure 2.12. The potential has valleys where the rims are higher and hills where the rims are smaller. The potential reflects the asymmetry of the ring. In the x,y-plane the top view of the ring of figure 2.12 is shown.

Structural Characterization Partial sumary

- Ring shape is preserved after capping
- Drastic reduction in vertical size
- Knowledge of realistic distribution of Indium

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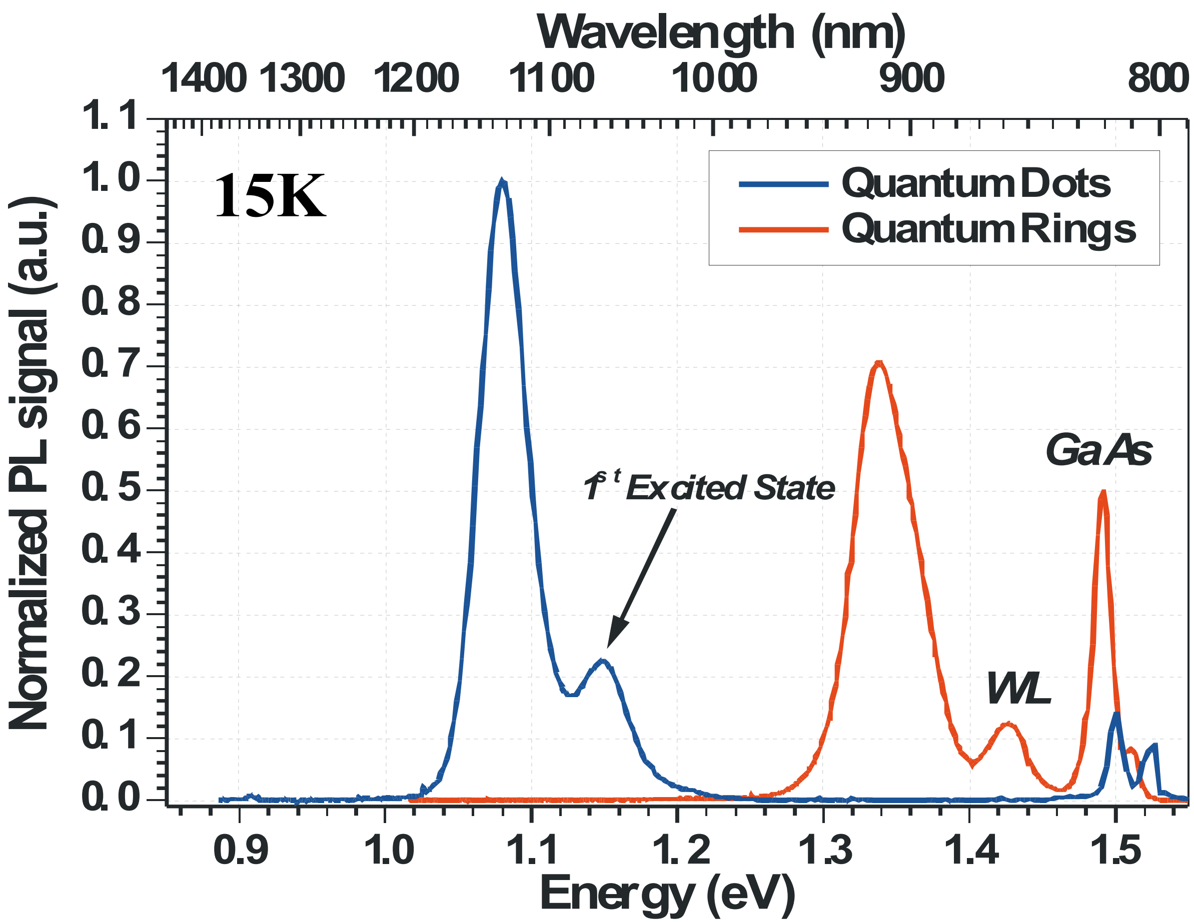
Tuning of emission



- Large change in Optical properties due to vertical confinement.
- Tunability of the nanostructures properties…Perfect for device applications!!

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QUANTUM…OK
but… Rings or small Dots?
Aharonov – Bohm Effect

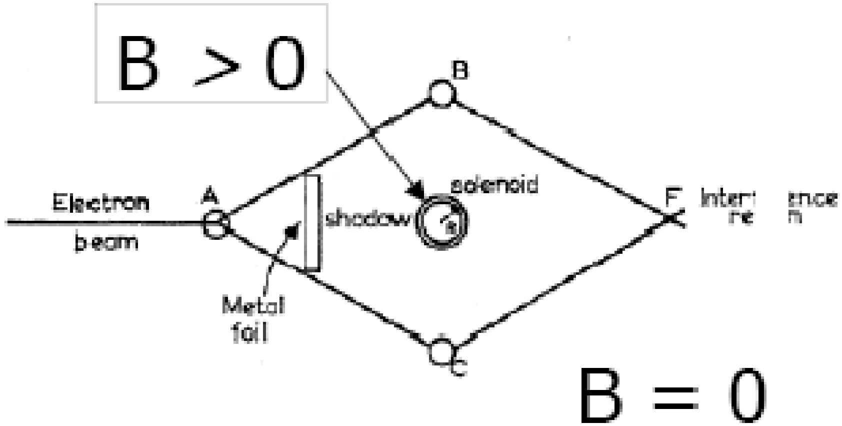
SECOND SERIES, VOL. 115, NO. 3 AUGUST 1, 1959

Significance of Electromagnetic Potentials in the Quantum Theory

Y. AHARONOV AND D. BOHM
H. H. Wills Physics Laboratory, University of Bristol, Bristol, England

(Received May 28, 1959; revised manuscript received June 16, 1959)

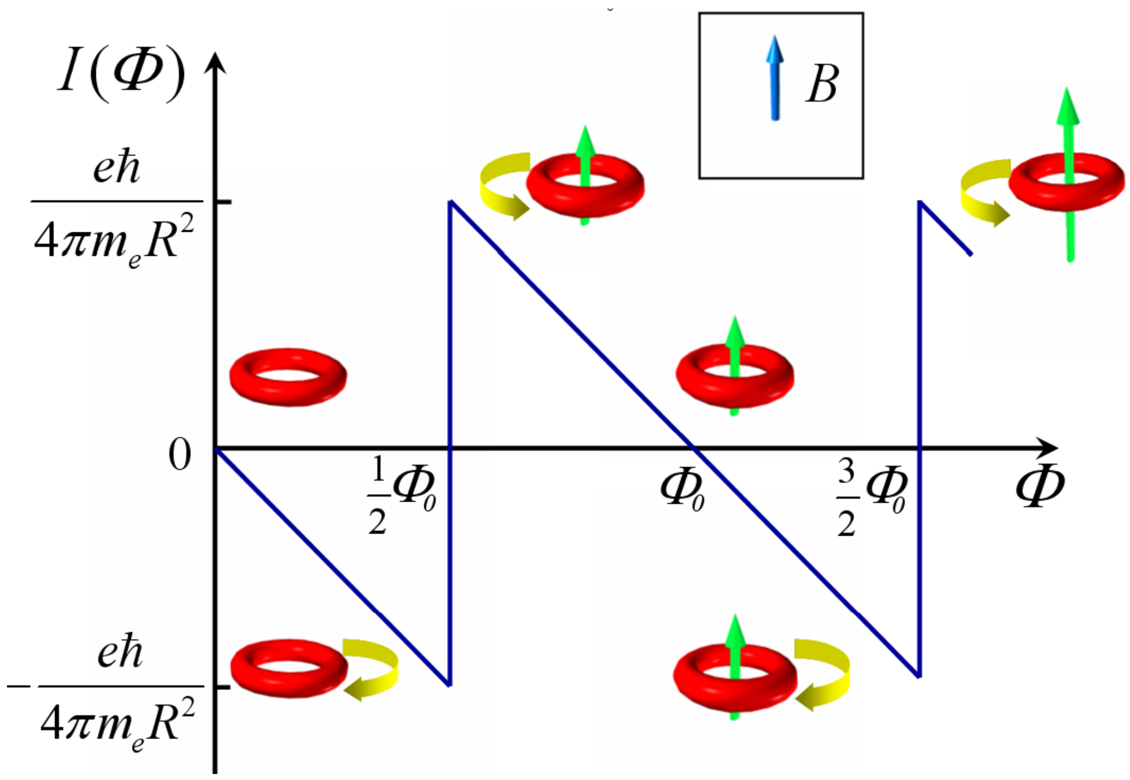
In this paper, we discuss some interesting properties of the electromagnetic potentials in the quantum domain. We shall show that, contrary to the conclusions of classical mechanics, there exist effects of potentials on charged particles, even in the region where all the fields (and therefore the forces on the particles) vanish. We shall then discuss possible experiments to test these conclusions; and, finally, we shall suggest further possible developments in the interpretation of the potentials.



$$\psi=\psi_1^0 e^{-iS_1/\hbar}+\psi_2^0 e^{-iS_2/\hbar},$$

$$H=\frac{[\mathbf{P}-(e/c)\mathbf{A}]^2}{2m}.$$

$$\Delta S/\hbar=-\frac{e}{c\hbar}\oint \mathbf{A}\cdot d\mathbf{x},$$

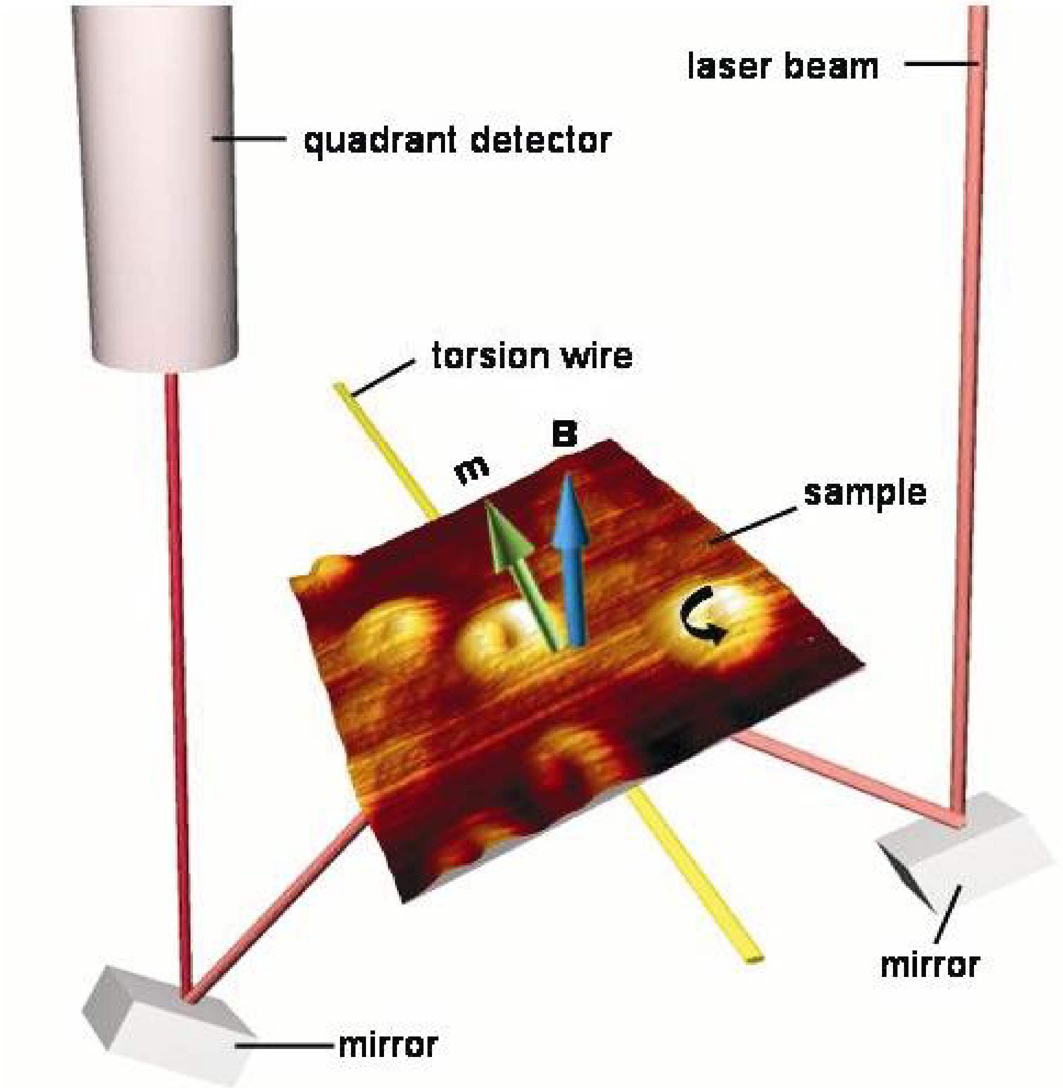


The persistent current *I(Φ)* of a ring as function of magnetic flux *Φ*. The Aharonov-Bohm effect implies that all physical properties of a 1D quantum ring of radius *R* in a magnetic field *B* are periodic functions of the enclosed magnetic flux with period Φ_0=h/e (the flux quantum)

At *B* =0 there is no persistent current in the ring. At small *B* the ground state has zero orbital momentum ($\ell = 0$), and to compensate for the magnetic flux that penetrates the ring, a (diamagnetic) persistent current appears in the ring (yellow arrow). At a magnetic field for which $\Phi = ½\Phi_0$ the orbital momentum of the ground state ℓ changes from *0* to *1*, together with an abrupt change in direction of the persistent current. For a ring with radius 11.5 nm the value of $½\Phi_0$ corresponds to a magnetic field of *B*=5 T. With further increasing *B* the persistent current decreases linearly and is zero again at $\Phi = \Phi_0$, when the ring encloses precisely one flux quantum (green arrow). This behaviour repeats itself periodically and each time the flux equals $(\ell+½)\Phi_0$, ℓ is increased by 1, a jump in the magnetic moment occurs with magnitude $\mu B/m^*$.

Magneto-Torsion experiments

The sample (7x8 mm²) is mounted onto a thin torsion wire (yellow). In a magnetic field *B* (Blue arrow), the induced magnetization of the sample *M* (green arrow) results in a torque which tends to rotate the sample, trying to align *M* and *B*. This optically detected rotation is counteracted by sending a current through a feedback coil of known area, located underneath the sample. The current through the feedback coil is a quantitative measure of *M*



- **Up to 15 Teslas**
- **T=1.2 K**

Oscillatory Persistent Currents in Self-Assembled Quantum Rings

N. A. J. M. Kleemans,[1] I. M. A. Bominaar-Silkens,[2] V. M. Fomin,[1,3,4] V. N. Gladilin,[3,4] D. Granados,[5] A. G. Taboada,[5] J. M. García,[5] P. Offermans,[1] U. Zeitler,[2] P. C. M. Christianen,[2] J. C. Maan,[2] J. T. Devreese,[1,3] and P. M. Koenraad[1]

[1]*PSN, COBRA, Eindhoven University of Technology, The Netherlands*
[2]*HFML, IMM, Radboud University Nijmegen, The Netherlands*
[3]*TFVS, Universiteit Antwerpen, Belgium*
[4]*FSM, Universitatea de Stat din Moldova, Chisinau, Moldova*
[5]*CSIC, Instituto de Microelectrónica de Madrid, Spain*
(Received 14 March 2007; published 5 October 2007)

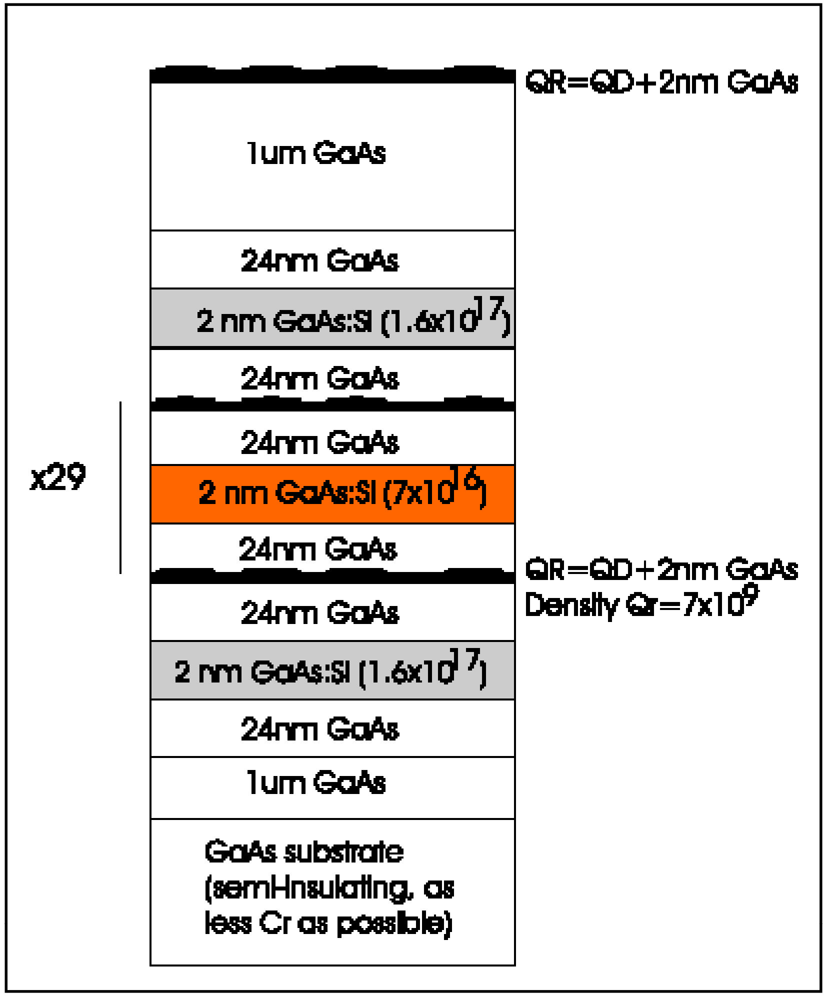
We report the direct measurement of the persistent current carried by a single electron by means of magnetization experiments on self-assembled InAs/GaAs quantum rings. We measured the first Aharonov-Bohm oscillation at a field of 14 T, in perfect agreement with our model based on the structural properties determined by cross-sectional scanning tunneling microscopy measurements. The observed oscillation magnitude of the magnetic moment per electron is remarkably large for the topology of our nanostructures, which are singly connected and exhibit a pronounced shape asymmetry.

DOI: 10.1103/PhysRevLett.99.146808 PACS numbers: 73.21.La, 73.23.Ra, 78.67.Hc

Magneto-Torsion
Design and growth of sample

MBE Growth at IMM

- High uniformity <10% (Critical!)
- High density→ 29 layers stacked QR
- 1-2e per QR → Modulation doping



Theoretical approach

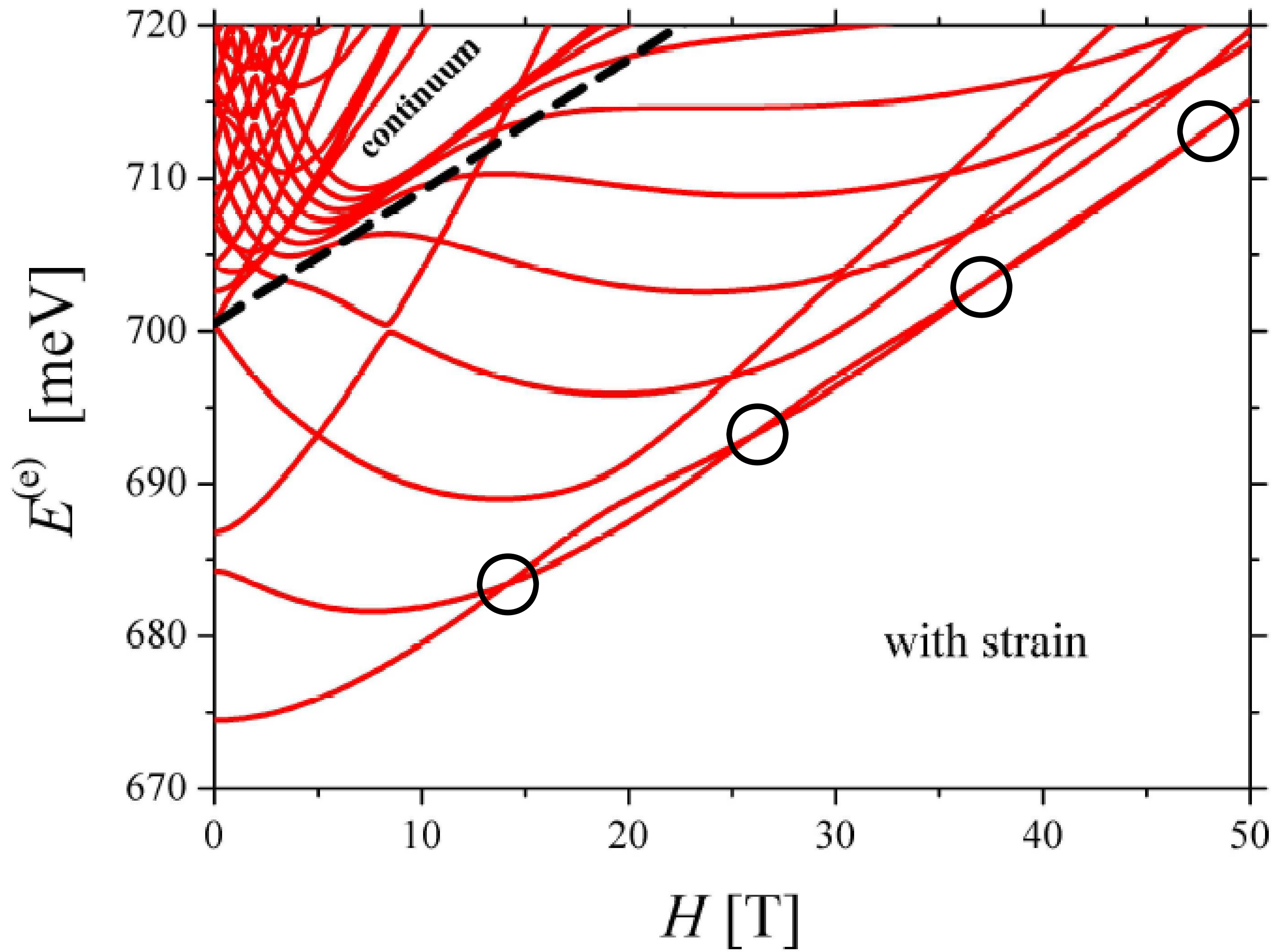
Prof. Devreese, V. Fomin (vladimir.fomin@ua.ac.be) et al, Uni. Anwerpen

Based on the structural information from X-STM measurements on buried self-assembled InGaAs/GaAs quantum rings, we calculate the electron energy spectra and the magnetization as a function of the applied magnetic field.

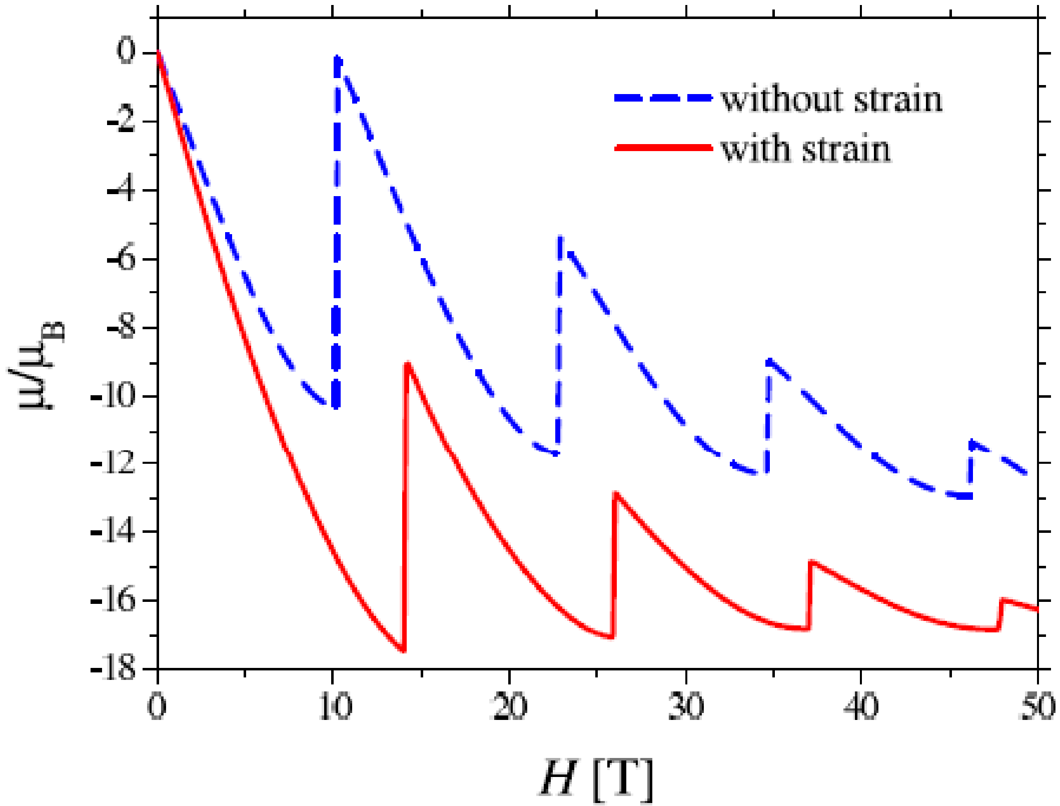
Since the lateral size of quantum rings substantially exceeds their height, we consider the lateral motion of electrons to be governed by the adiabatic potential related to the fast electron motion along the growth axis.

The electron states are calculated by diagonalizing the adiabatic Hamiltonian in the basis of in-plane wave functions.

Calculations on Energy levels



Theory: Magnetization



$$M = \frac{\partial F}{\partial B}\Big|_{N,T};$$

$$M = N\mu$$

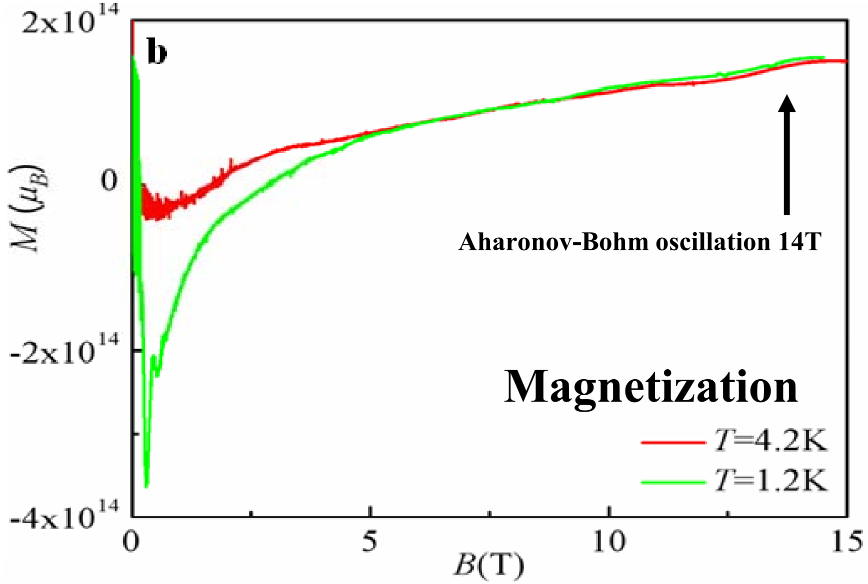
RESULTS: QR under Magnetic Field

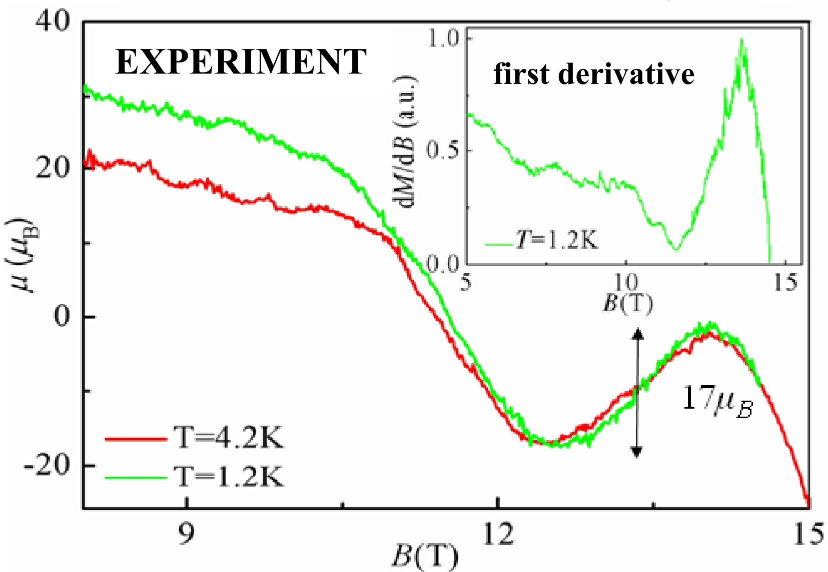
Magnetic moment of electrons in QR.

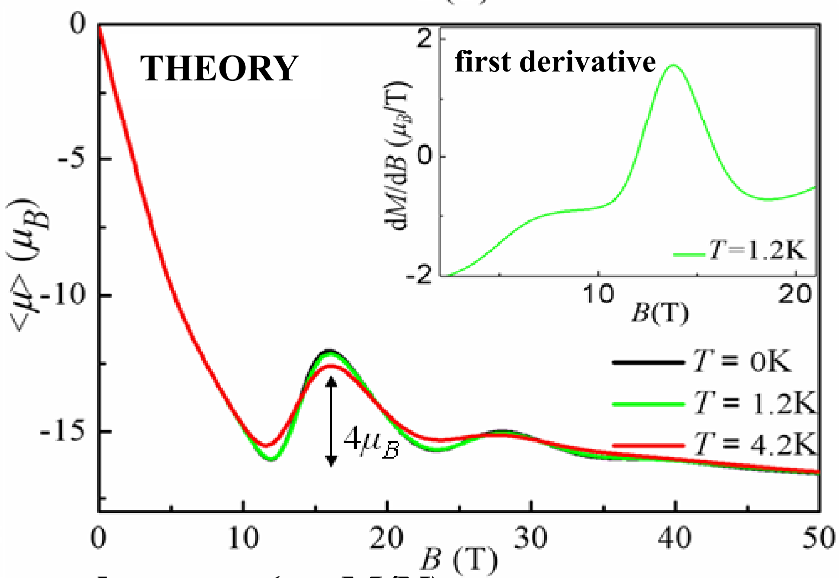
•Oscillation at 14 T

•Theory from realistic experimentally measured X- STM data

•Excellent agreement demonstrate persistent currents associated with RING geometry







Magnetic moment per electron, (μ=M/N)

Micro PL set up,

A.G.Taboada @ Eindhoven, NL

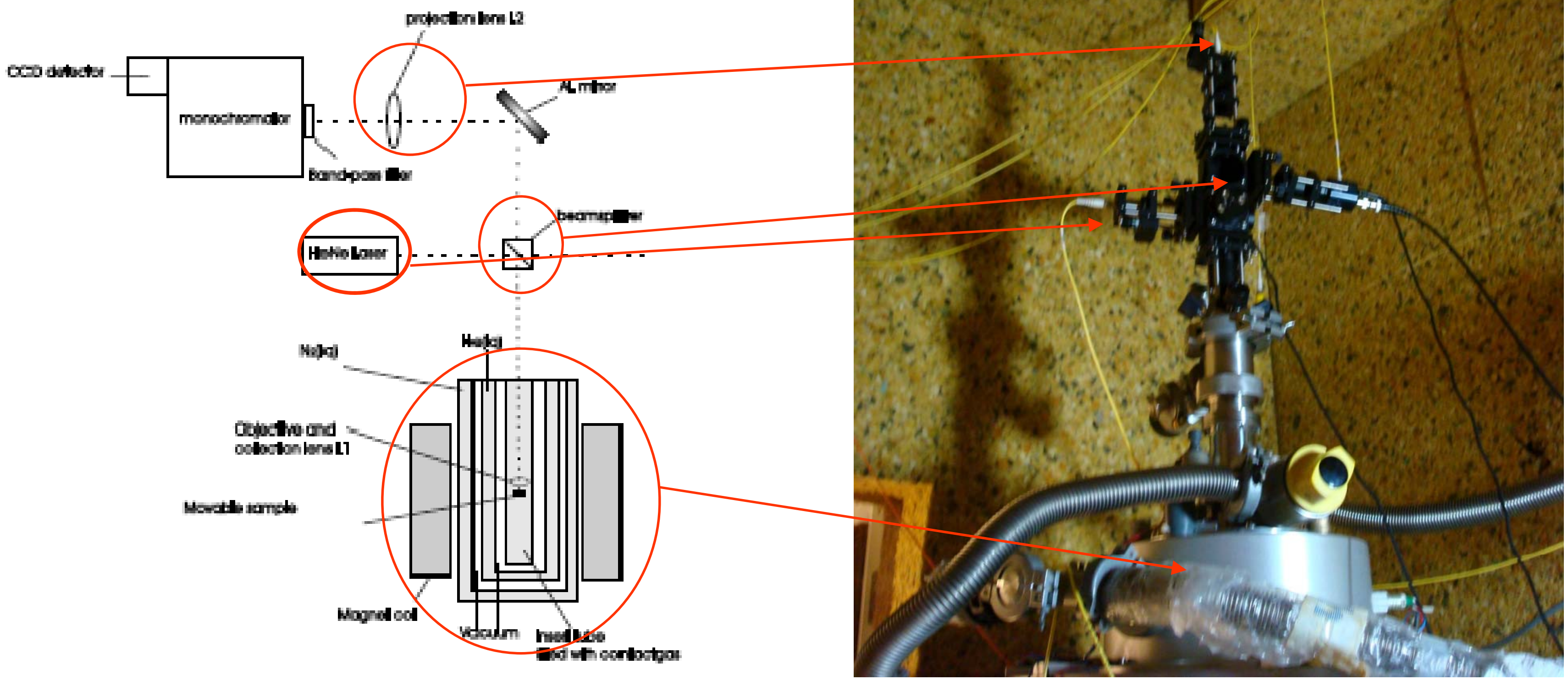
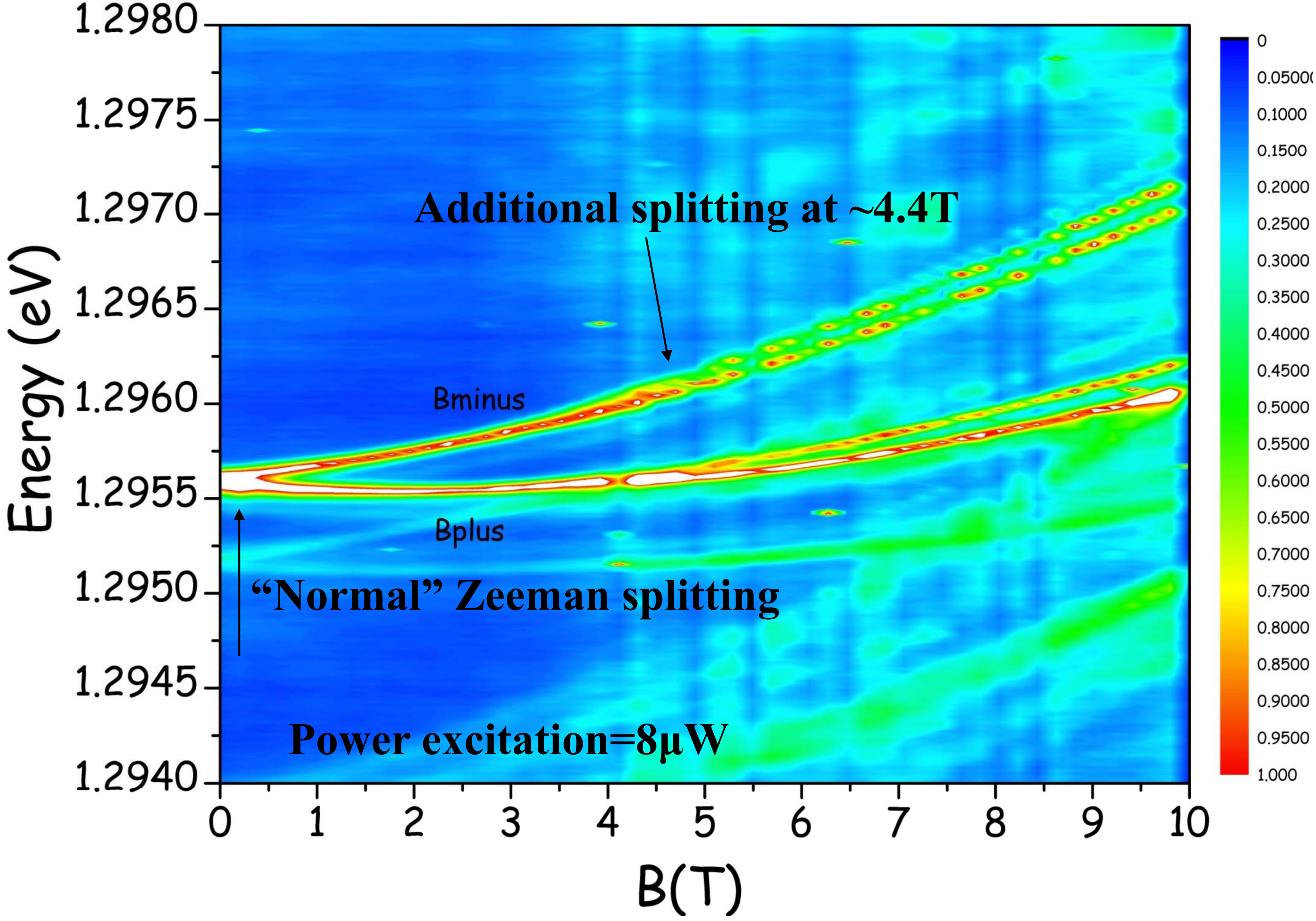


Figure 3.2: Schematic representation of the PL setup for measurements in magnetic field. A HeNe-laser (λ=632.8nm) excites carriers in the sample. The resulting PL is focused on a monochromator and measured with the use of an Si CCD detector. The sample is placed in a tube filled with contact gas. This tube is placed in the center of a bitter magnet.

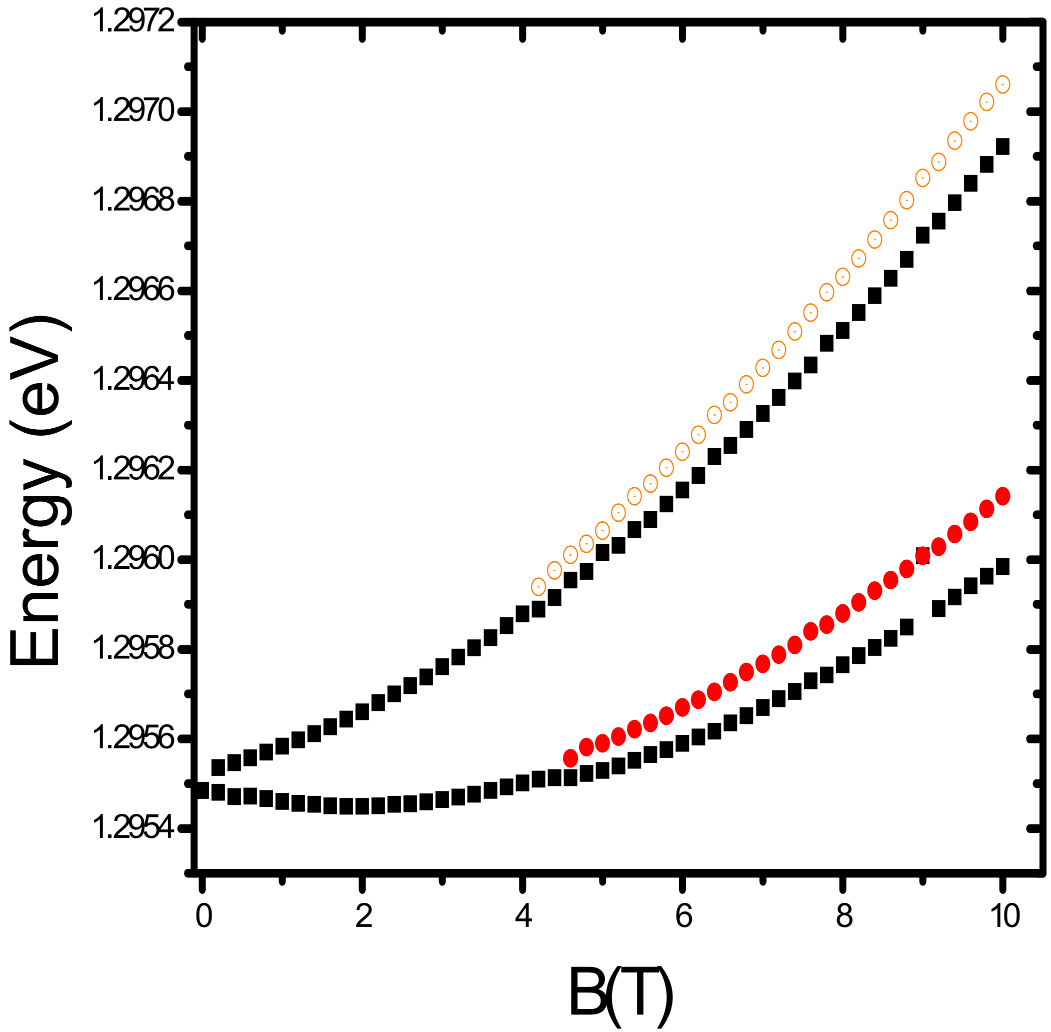
15 micro eV resolution with a triple monocromator triple

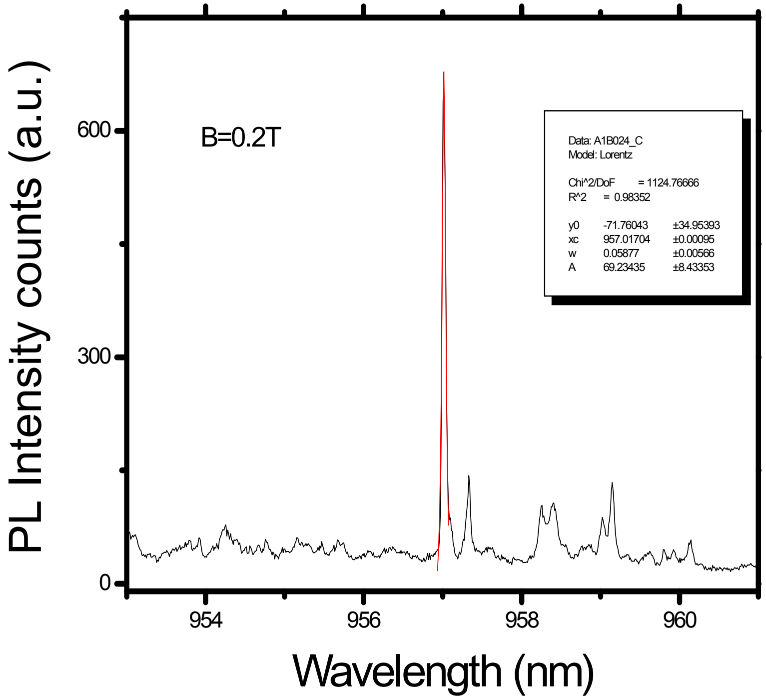
T=4.2, B_{max}=11T

Micro PL from one single Quantum Ring



Micro PL from one single Quantum Ring: Fitting

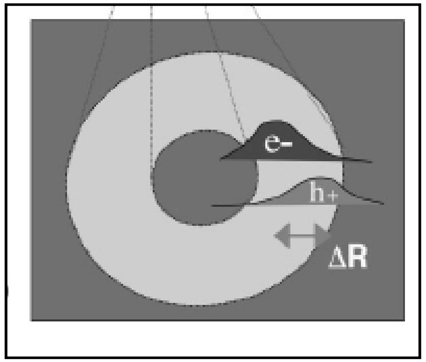




1 pixel=15μeV, FWHM=4-5 pixels

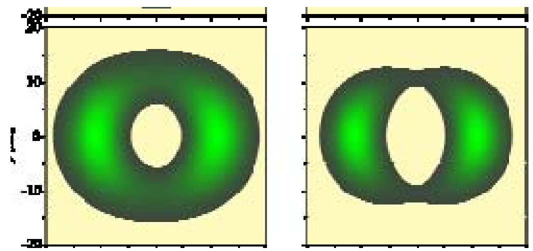
Possible explications

-Aharonov-Bohm effect: Capture of one quanta flux by the exciton due to the different radial sizes of the electron and the hole due to the ring geometry. Transition p_{hole}-to-$S_{electron}$



A.O. Govorov et al, PRB 66 (2002) 081309

-Magnetic field breaks the ring into two dots.



-Mixture of heavy-hole/ light hole due to breaks of symmetry rules by B. (Bayer et al…) But intensity distribution is very different.

Self Assembled Quantum Rings
Outline

- Intro...
- Growth of Self assembled Quantum Ring
- Structural Properties: XTEM & XSTM
- Optical properties: PL
- Magnetic Fields
  - Magneto-torsion
  - PL
- Conclusions

•**Quantum rings preserve shape after capping**

•**Key role of stress-free-state of In on growth of self assembled nanostructures**

•**Tunning of properties. Reduction in vertical size achieved in a controlled way**

•**Demonstrate the AB effect…**

Quantum Rings

- Conclusions

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Thank you for your attention