UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.998d - 24

Research Workshop on Condensed Matter Physics
30 June - 22 August 1997
MINIWORKSHOP ON
QUANTUM WELLS, DOTS, WIRES
AND SELF-ORGANIZING NANOSTRUCTURES
11 - 22 AUGUST 1997

"Far-Infrared and Capacitance Spectroscopy of Self-Assembled InAs Quantum Dots"

A. LORKE
Universitat Munchen
Sektion Physik
Geschwister Scholl Pl. 1
80539 Munchen
Germany

These are preliminary lecture notes, intended only for distribution to participants.

Far-Infrared and Capacitance Spectroscopy of Self-Assembled InAs Quantum Dots

A. Lorke
M. Fricke
B. T. Miller
R. J. Luyken
J. P. Kotthaus

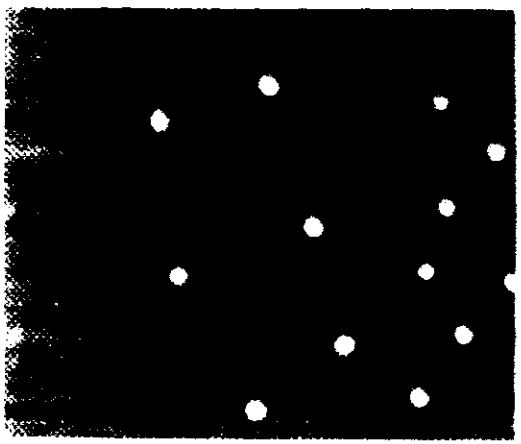
LMU München

G. Medeiros-Ribeiro
P. M. Petroff

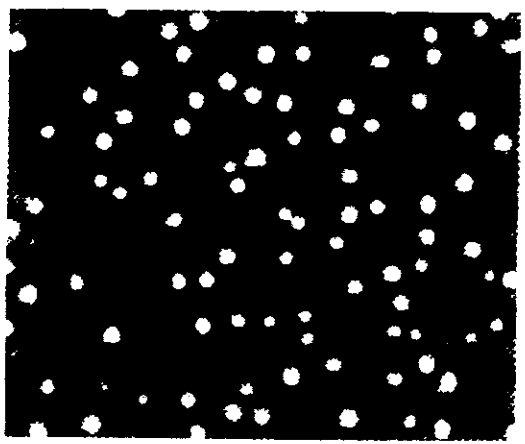
UC Santa Barbara

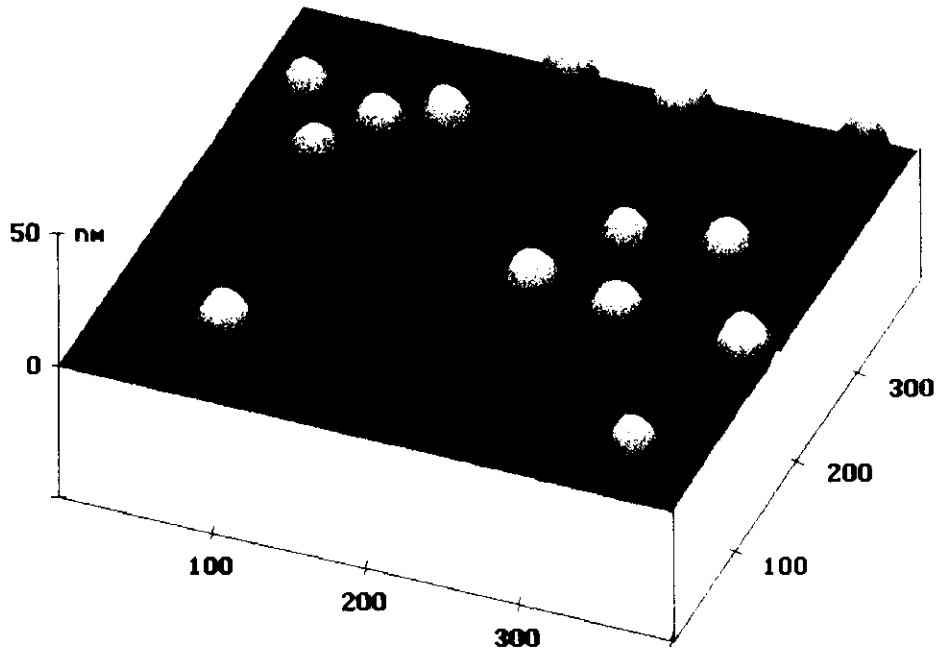
Stranski-Krastanow Growth Procedure

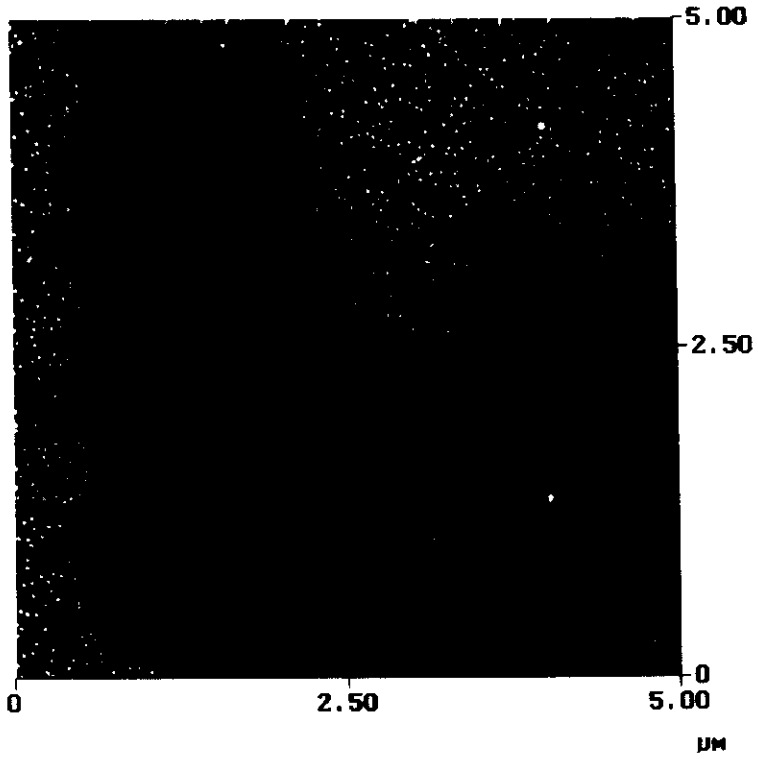
InAs on GaAs

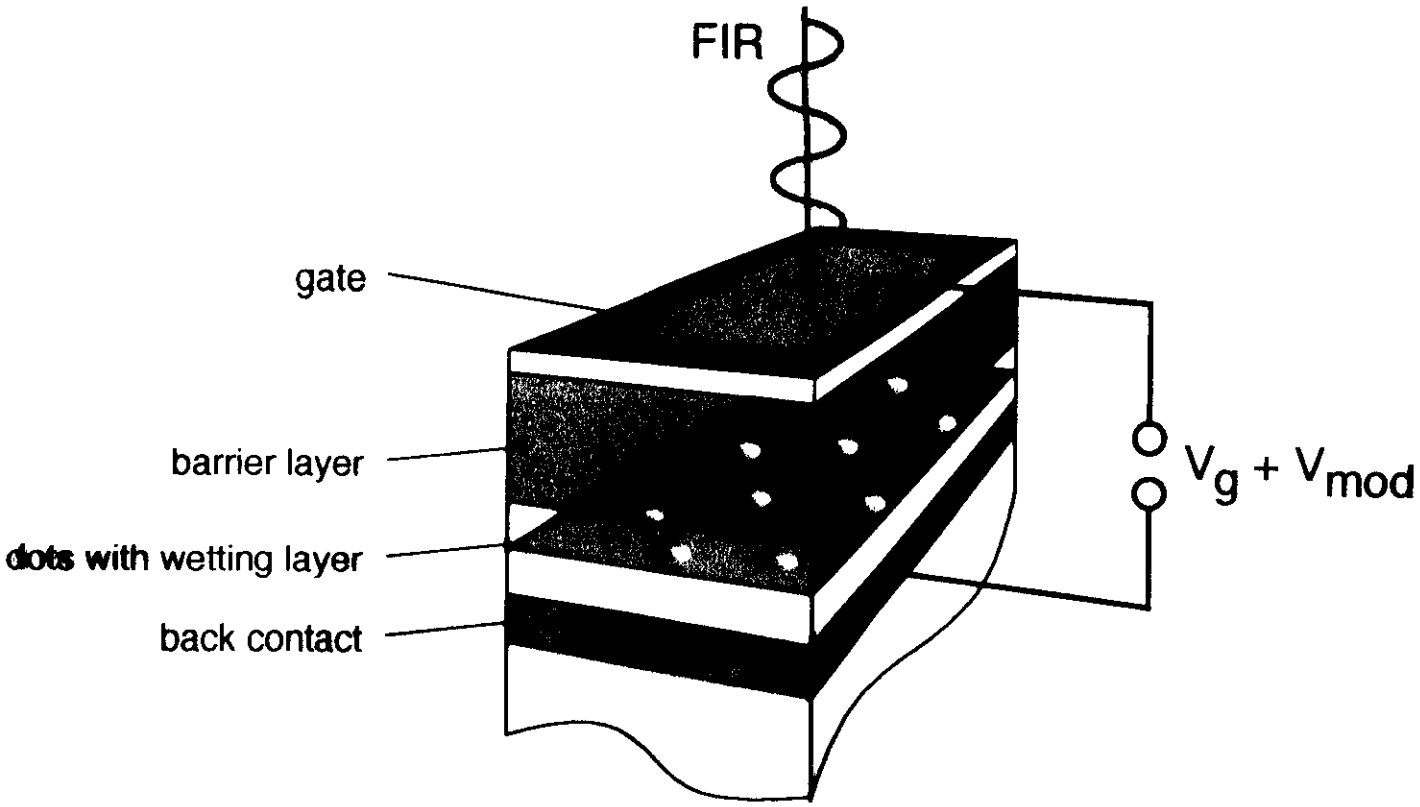


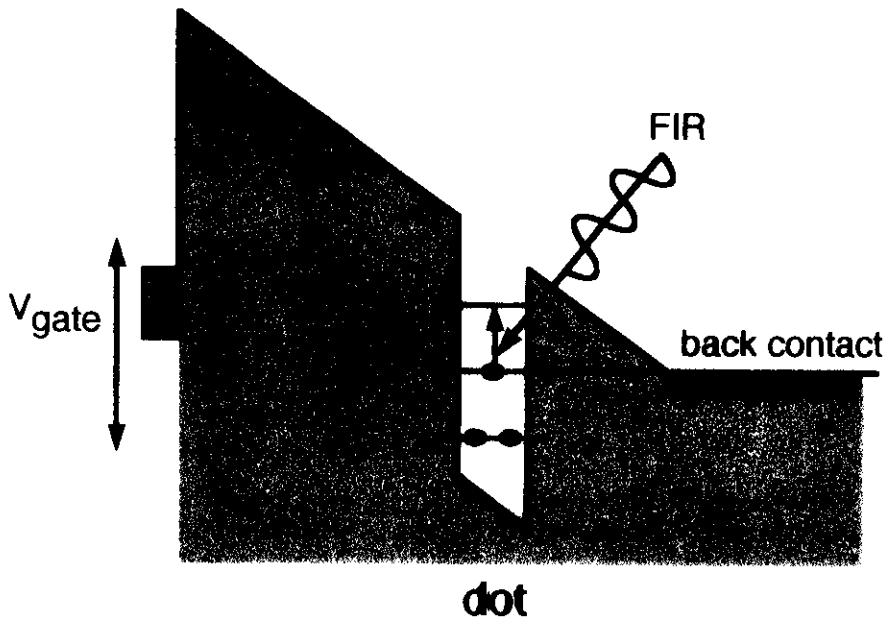
variable density
narrow size distribution
≈ 20 nm diameter
≈ 7 nm height



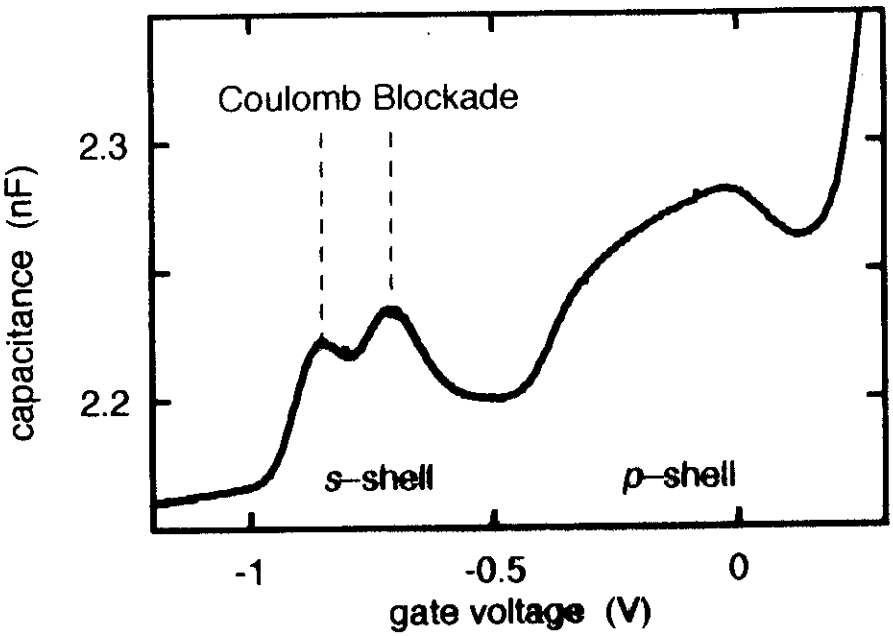

50
nm
0
100
200
300
100
200
300

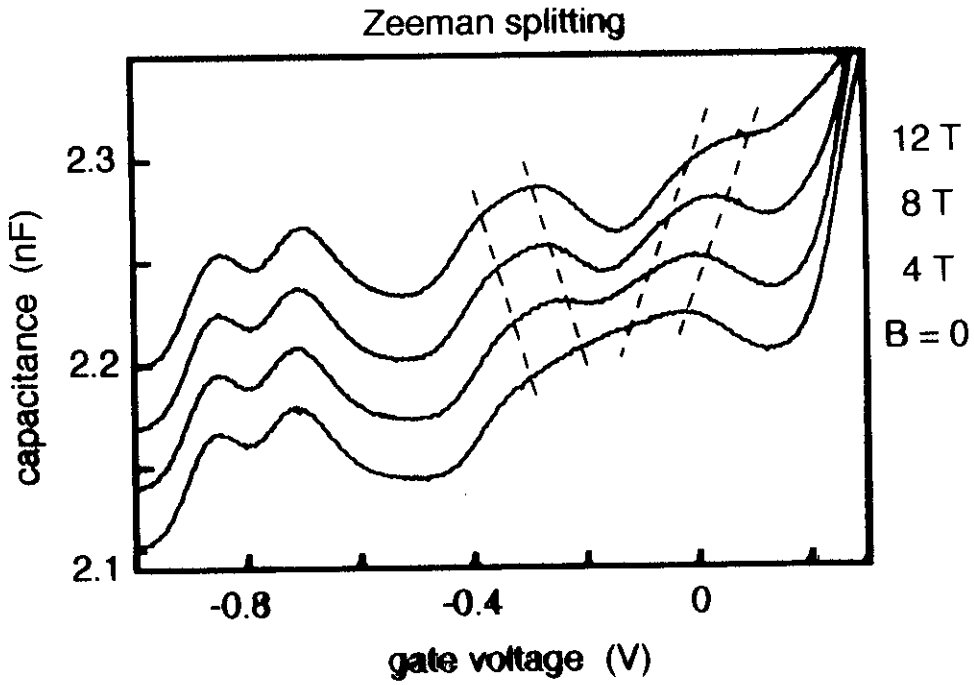

5.00
2.50
0
0
2.50
5.00
μm

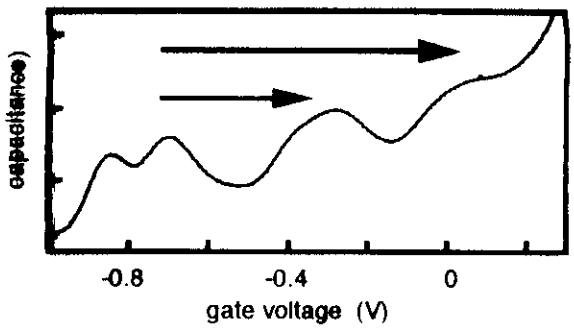

FIR
gate
barrier layer
dots with wetting layer
back contact
$V_g + V_{mod}$


FIR
V_{gate}
back contact
dot

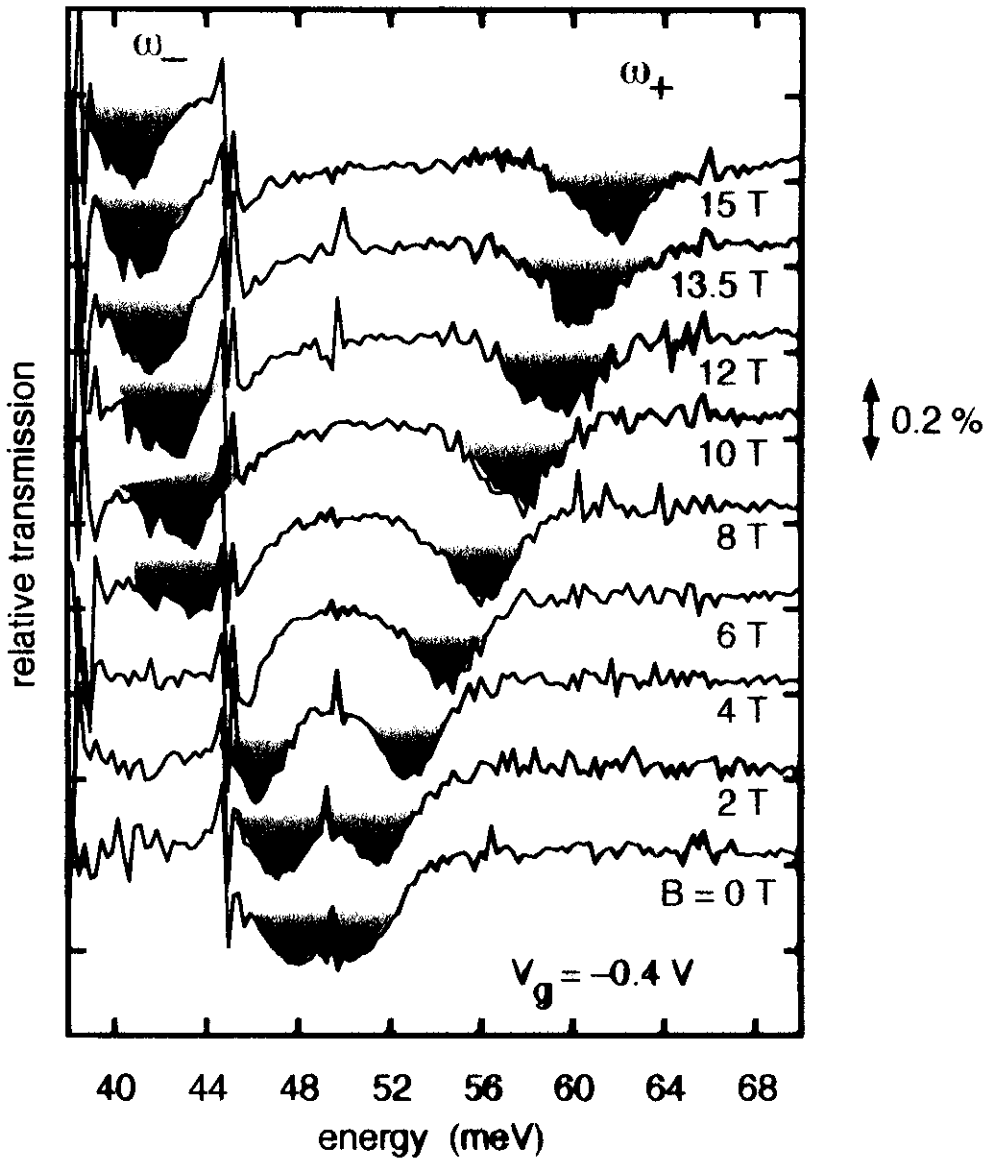
Capacitance Spectroscopy



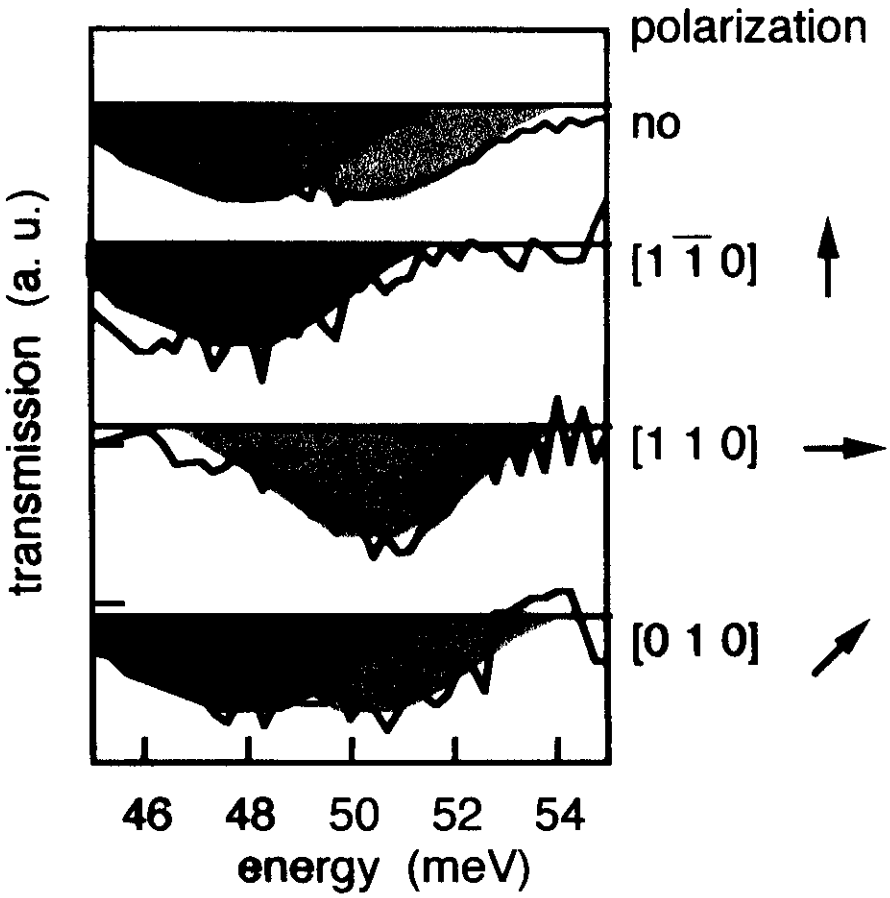




Far-infrared Spectroscopy



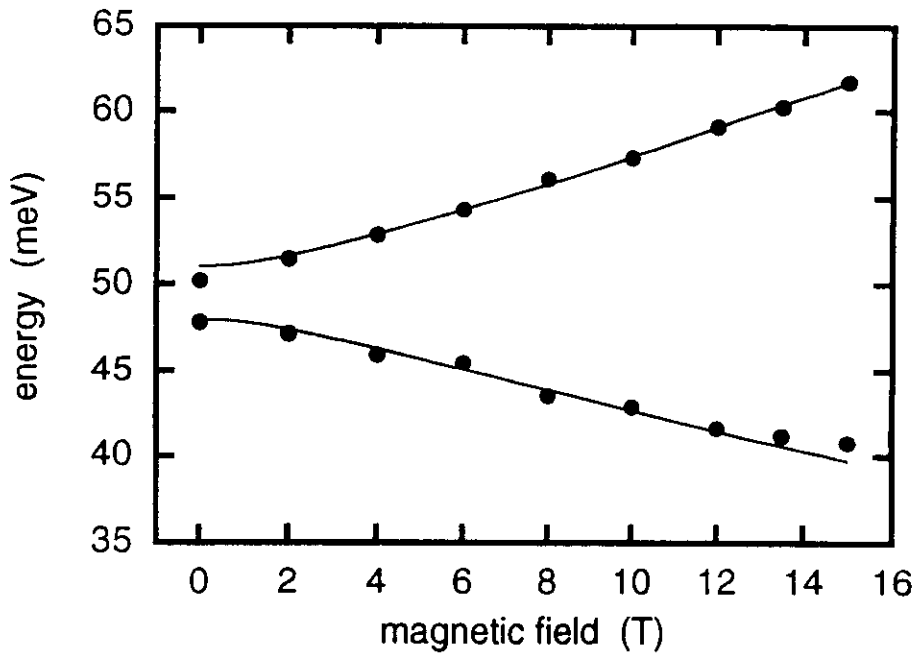
splitting of the dot mode at B = 0



corresponds to an **elongation** by 2 % along [1 $\bar{1}$ 0] (= 5 Å !)

other possible explanation: **symmetry breaking through piezo-electric effects** (**Grundmann *et al.***)

Dispersion of elliptic dots
w/ parabolic confinement



$\Rightarrow m^* = (0.080 \pm 0.002)\, m_e$

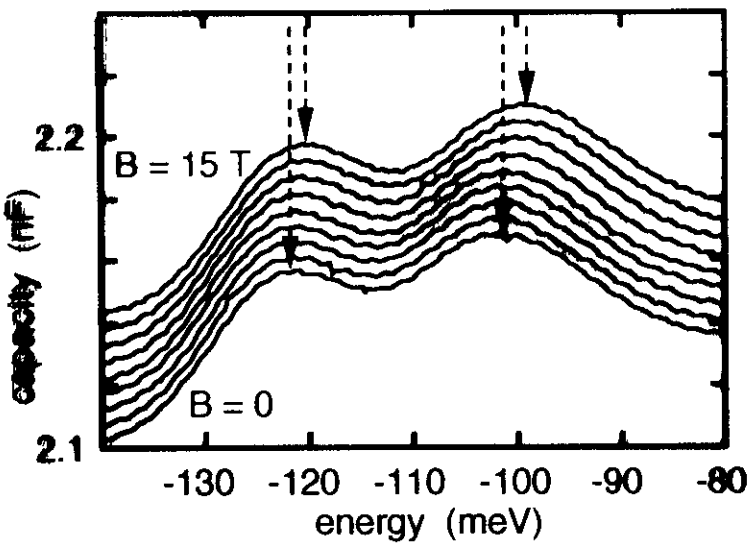
$m^*_{InAs} = 0.023\, m_e$

$m^*_{GaAs} = 0.067\, m_e$

2-Band k·p: $m^*_{InAs} = 0.079\, m_e$

non-parabolicity

Magnetic effects



$$E_{12} = 23\ \text{meV} = \frac{e^2}{4\pi\varepsilon\varepsilon_0 \ell}\sqrt{\frac{\pi}{2}}$$

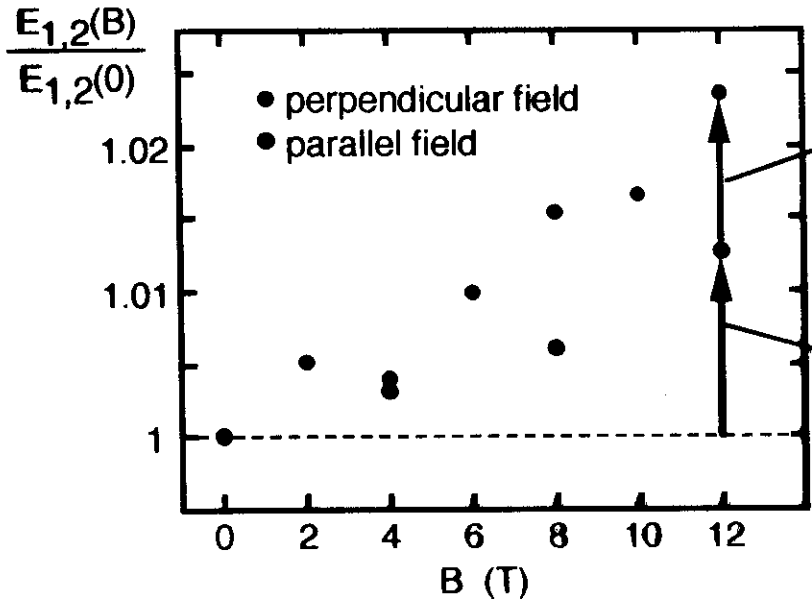
Capacitance

$\Rightarrow$ **ℓ_o = 6 nm**

$$\hbar\omega_0 = 50\ \text{meV},\quad \ell = \sqrt{\frac{\hbar}{m^*\omega_0}}$$

Far-Infrared

$\Rightarrow$ **ℓ_o = 4.4 nm**

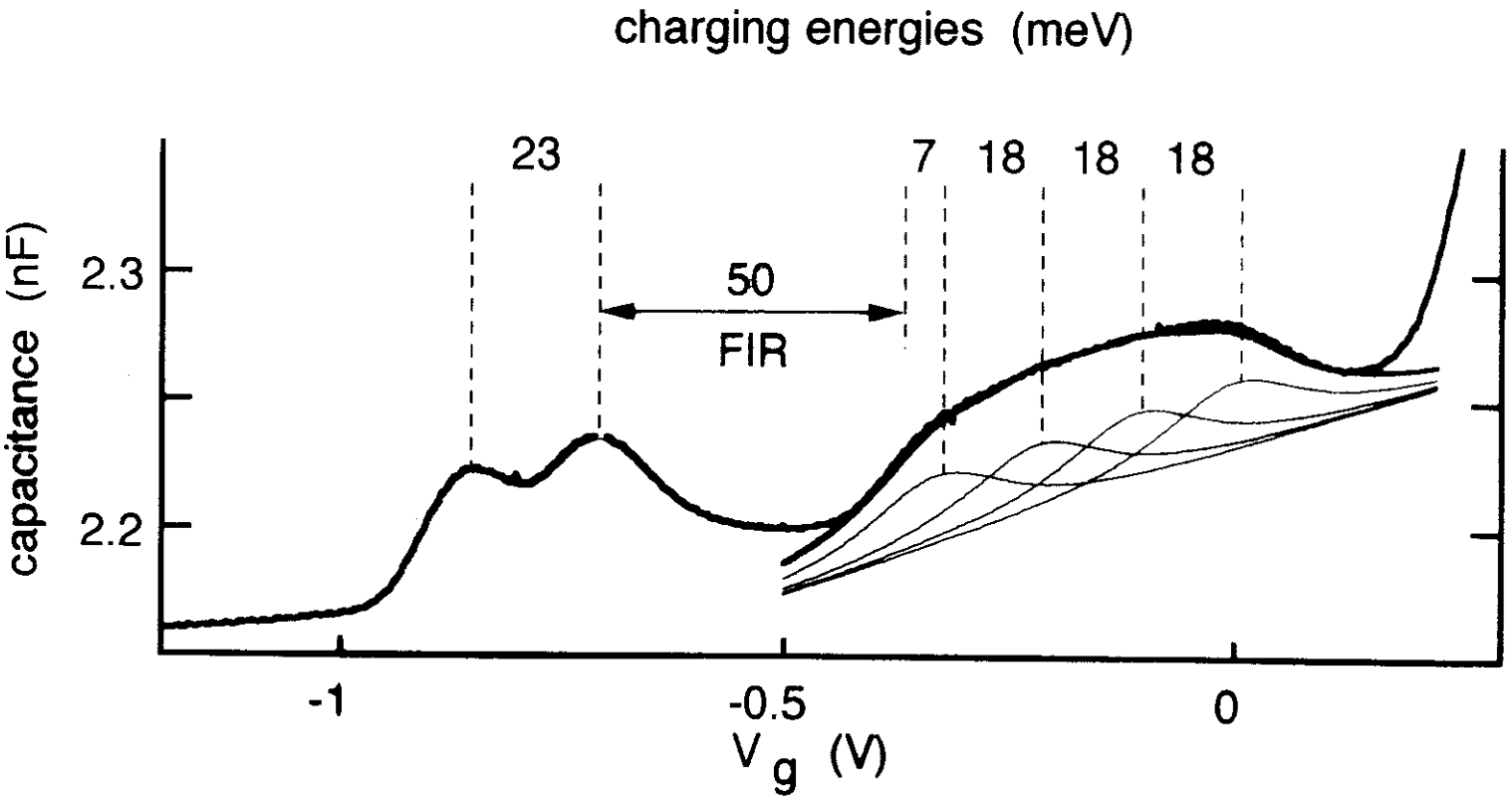


wave function compression

$$\ell^2 = \ell_0^2\sqrt{1 + \left(\frac{\omega_0}{2\omega_c}\right)^2}$$

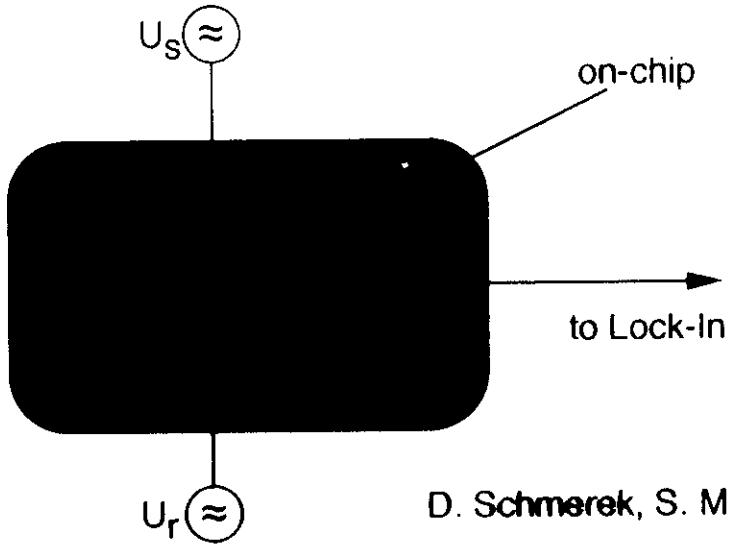
spin splitting

$\Rightarrow$ **$|g_{eff}| = 0.42$**

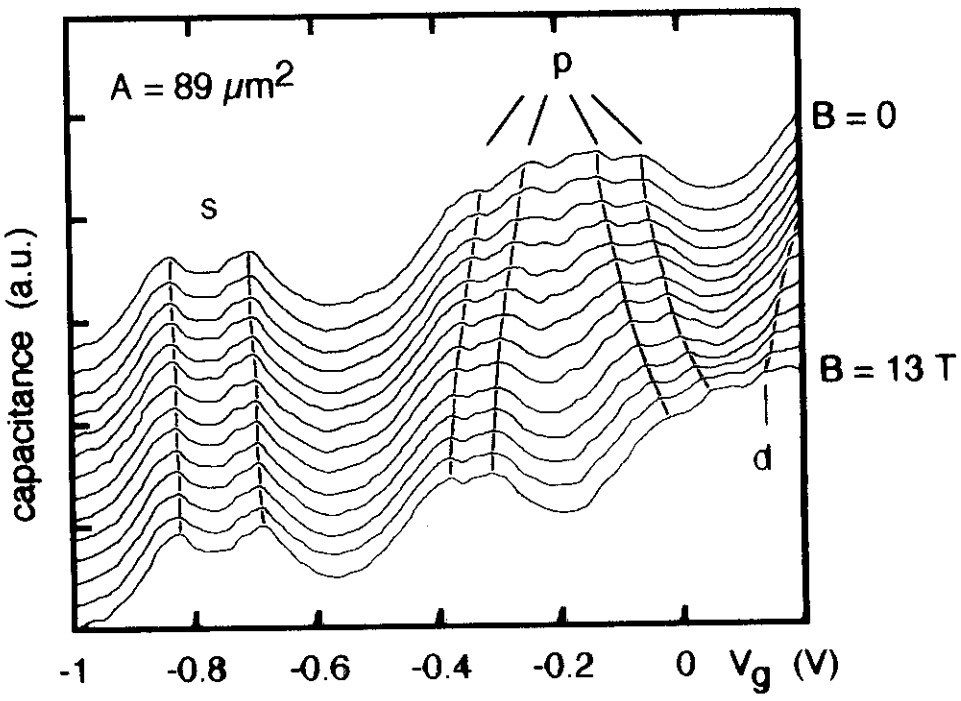


Influence of the shell structure on the Coulomb charging energies

Local Capacitance Spectroscopy



D. Schmerek, S. Manus, W. Hansen



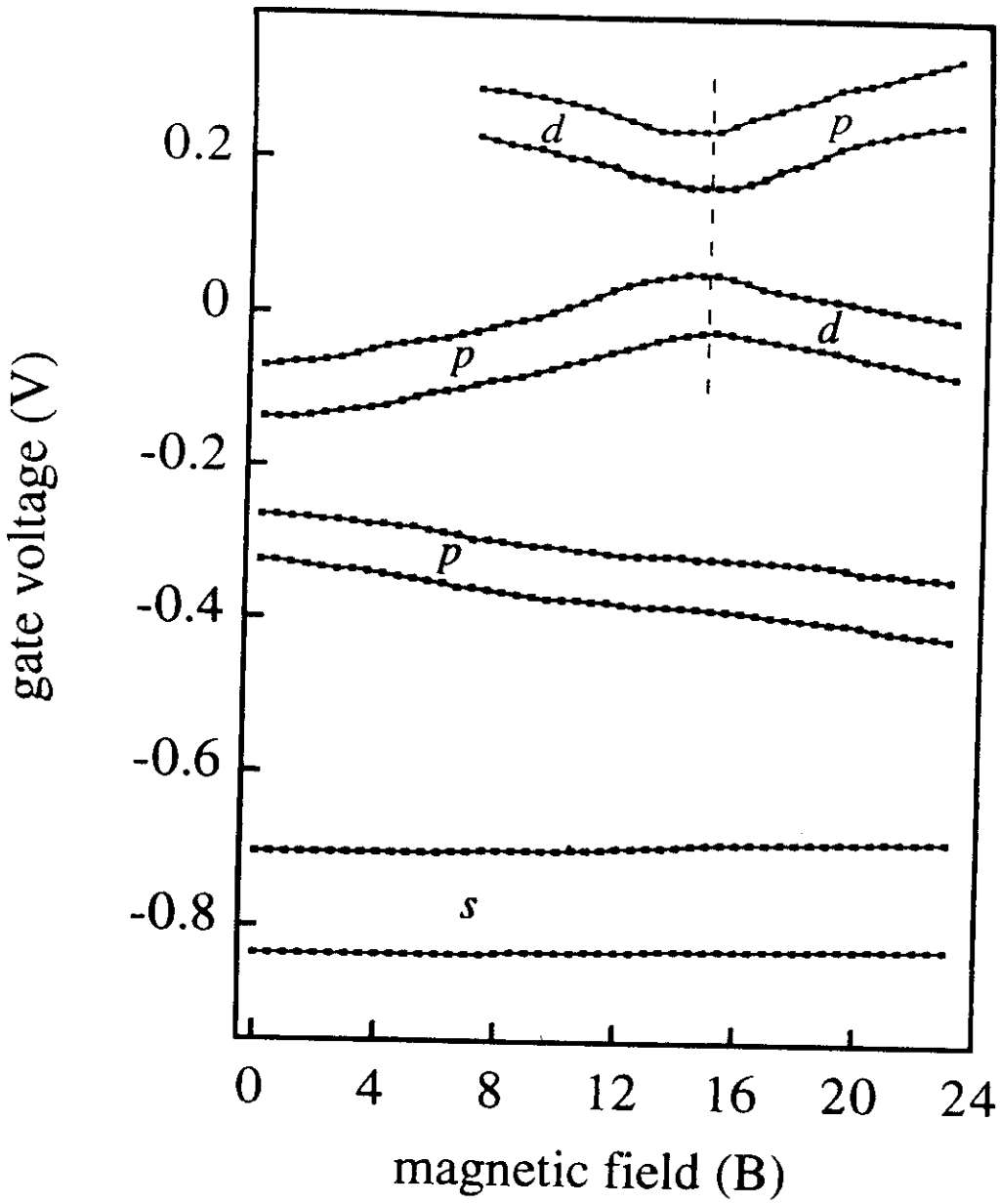
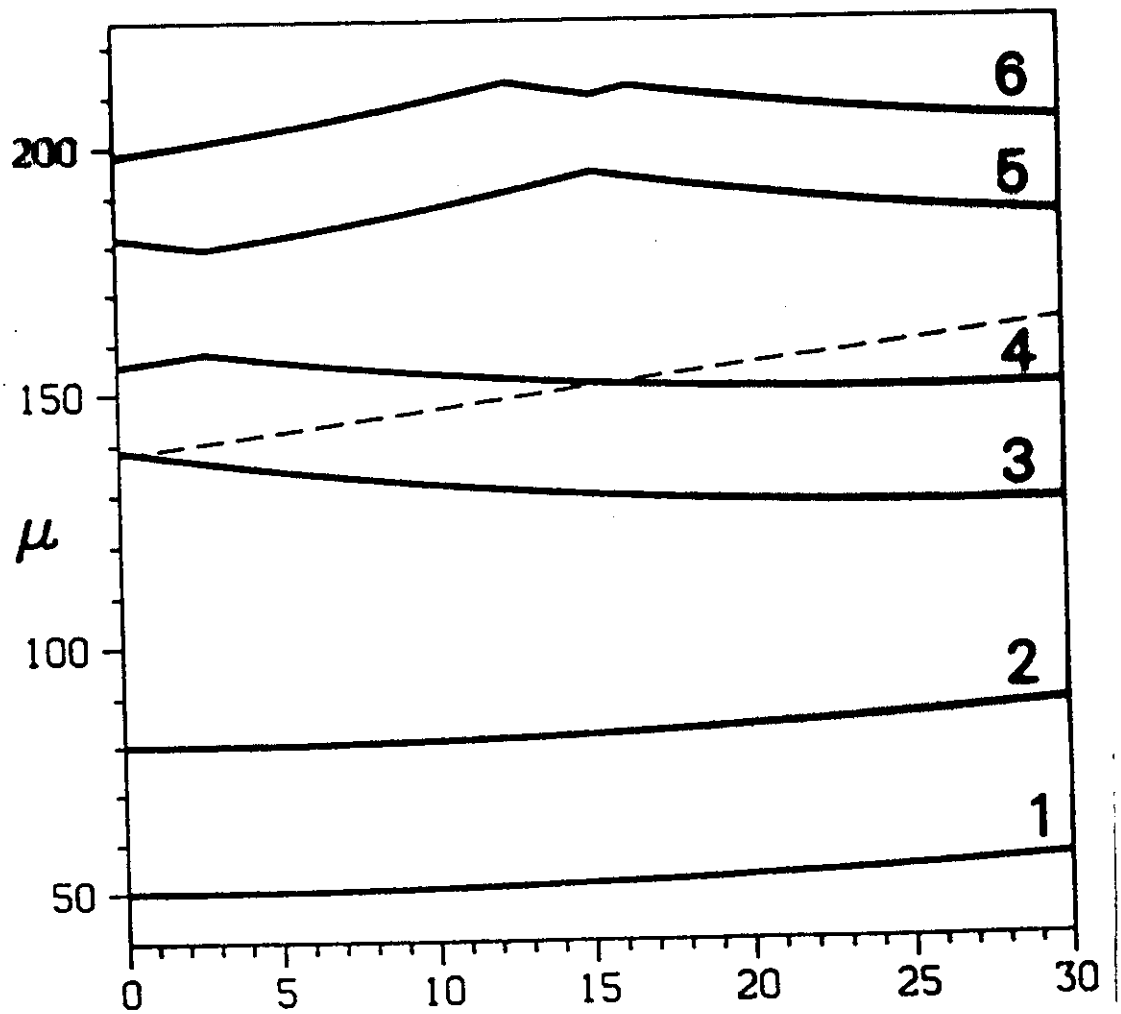
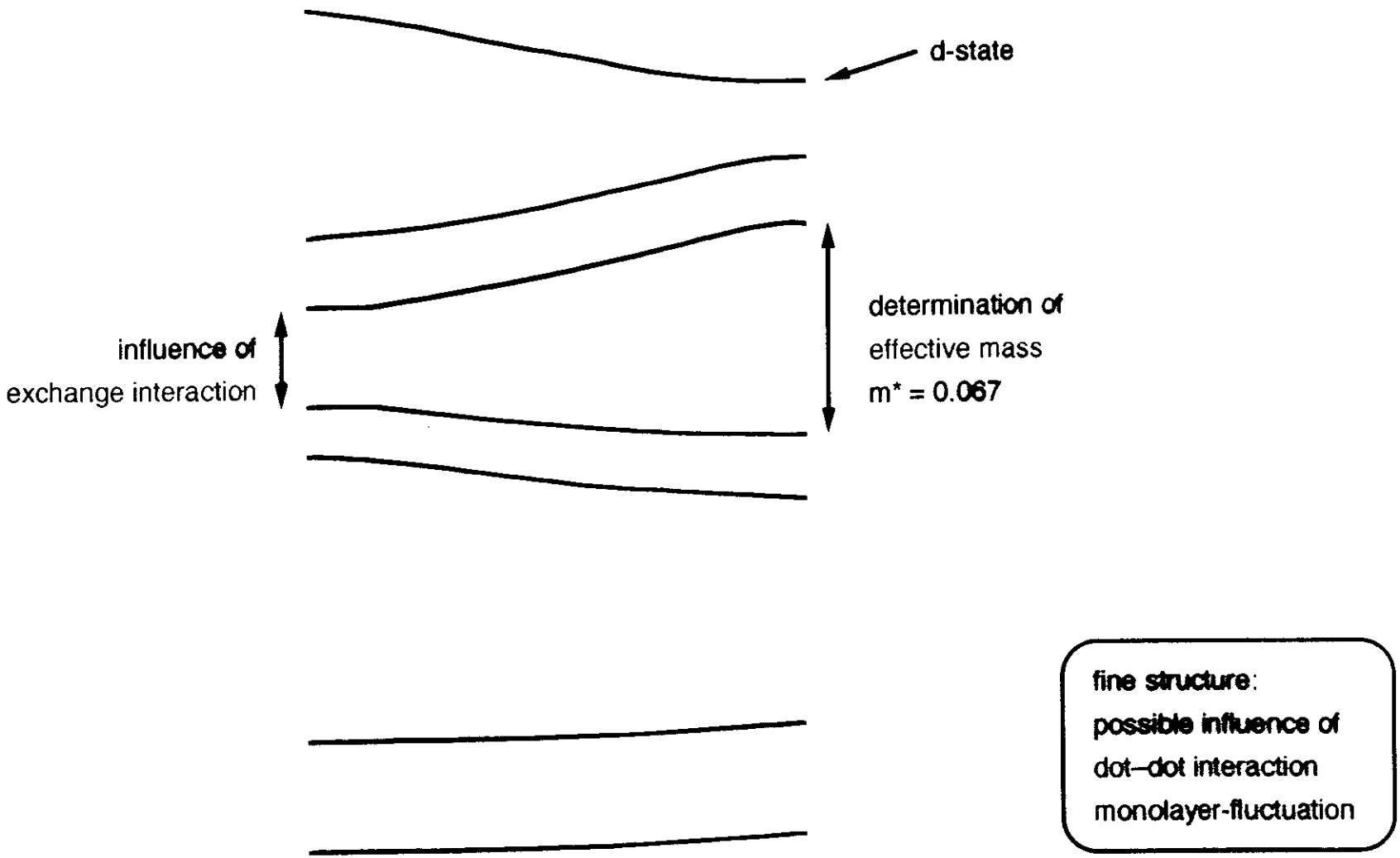

0.2
0
-0.2
-0.4
-0.6
-0.8
gate voltage (V)
d
p
p
d
p
s
0
4
8
12
16
20
24
magnetic field (B)

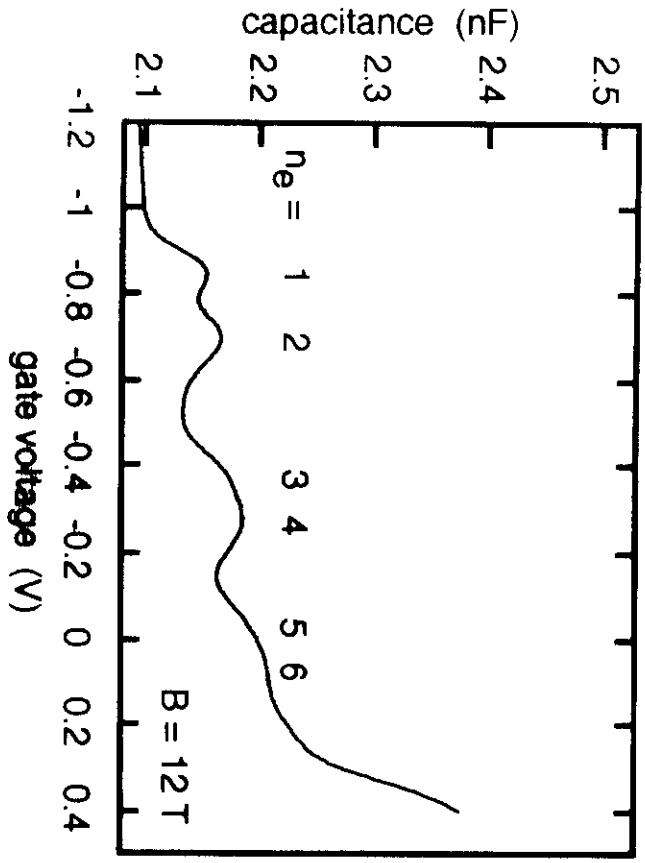
Fig 3b

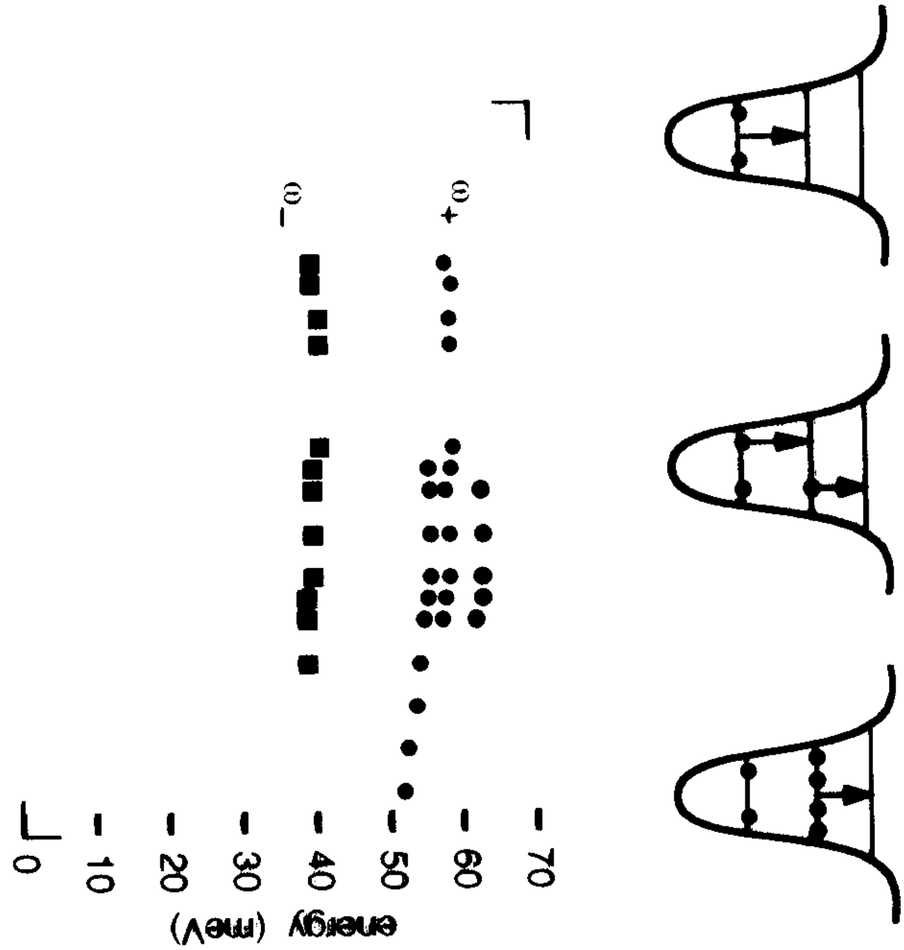


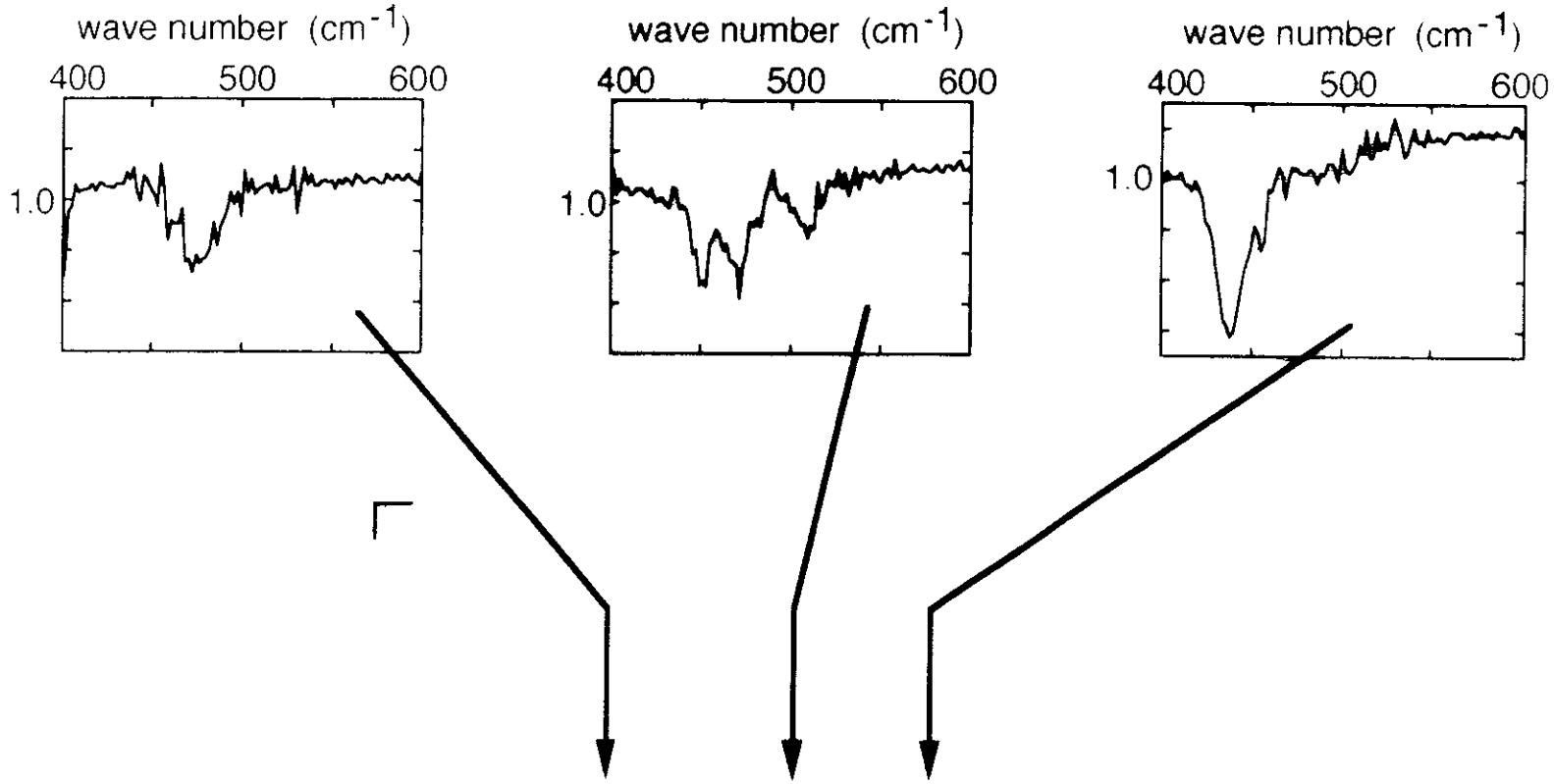
A. Wójs & P. Hawrylak, Phys. Rev. B 53 10841 (96)

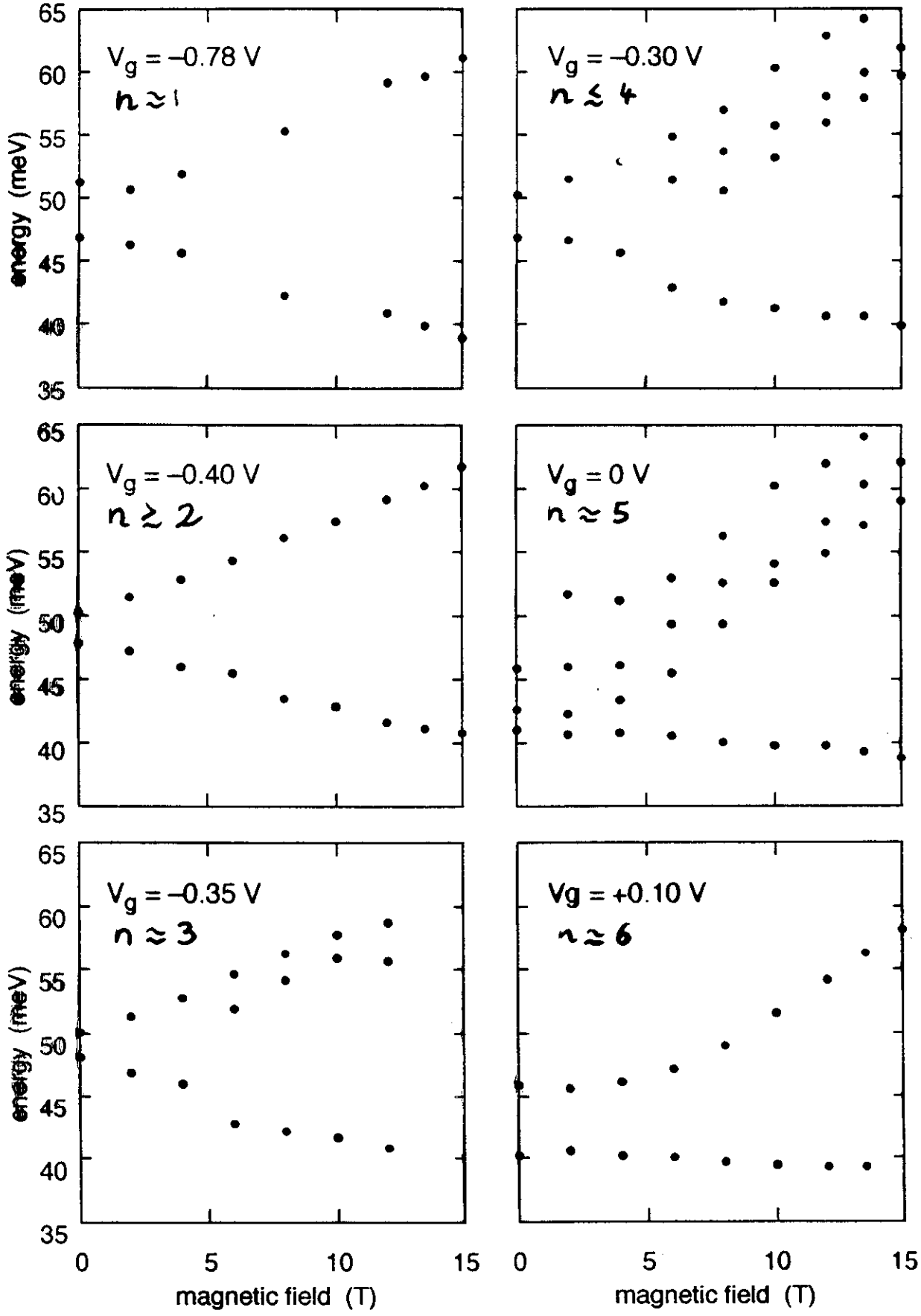

50 meV
0
5
10
B (T)


d-state
influence of
exchange interaction
determination of
effective mass
m* = 0.067
fine structure:
possible influence of
dot–dot interaction
monolayer-fluctuation

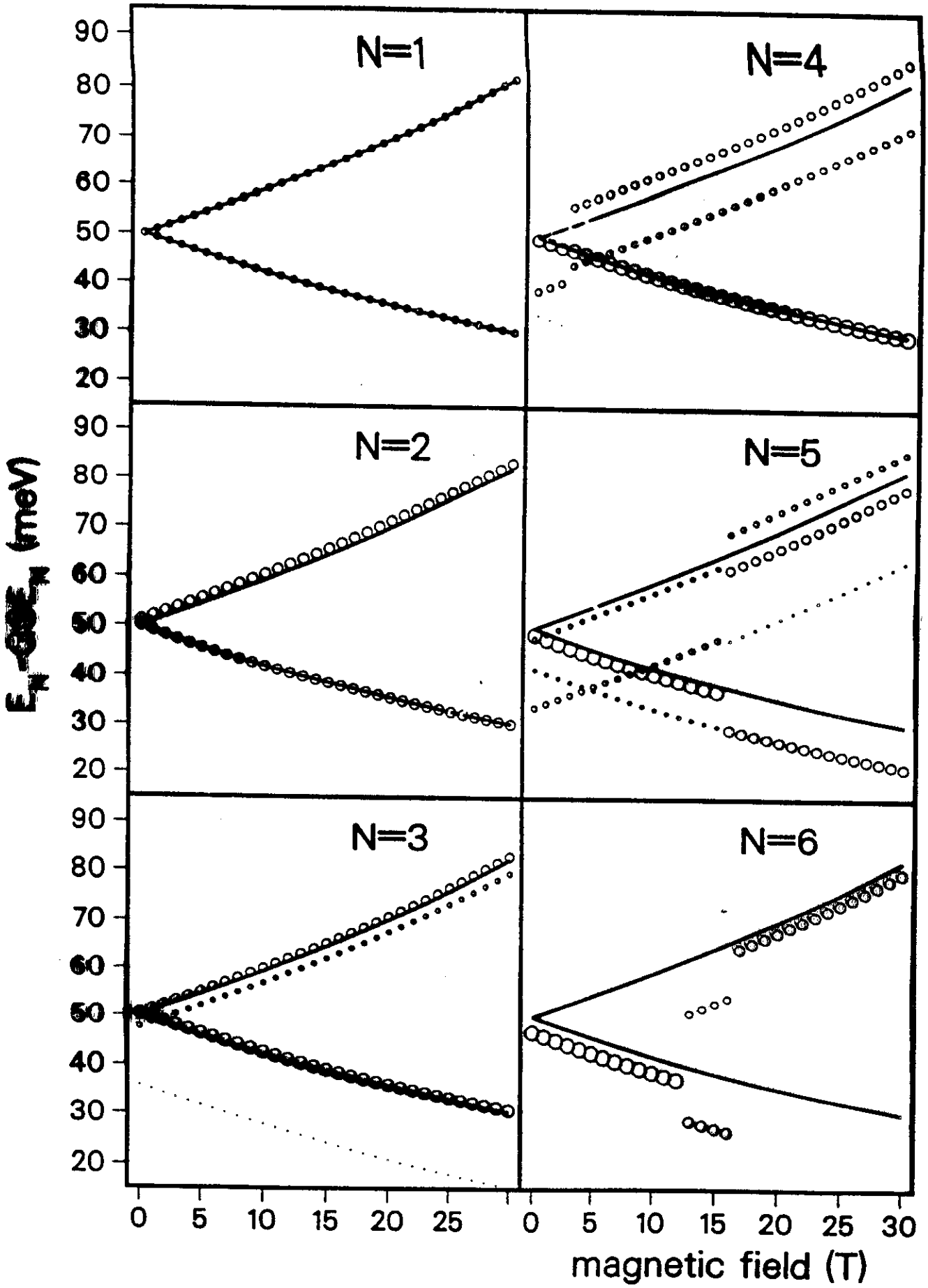

capacitance (nF)
2.1
2.2
2.3
2.4
2.5
n_e = 1 2 3 4 5 6
B = 12 T
-1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4
gate voltage (V)


ω+
ω−
energy (meV)
0
10
20
30
40
50
60
70


wave number (cm-1)
400
500
600
1.0
wave number (cm-1)
400
500
600
1.0
wave number (cm-1)
400
500
600
1.0


V_g = –0.78 V
$n \approx 1$
V_g = –0.30 V
$n \lesssim 4$
V_g = –0.40 V
$n \gtrsim 2$
V_g = 0 V
$n \approx 5$
V_g = –0.35 V
$n \approx 3$
Vg = +0.10 V
$n \approx 6$
energy (meV)
65
60
55
50
45
40
35
0
5
10
15
magnetic field (T)

A. Wojs and P. Hawrylak, Phys. Rev. B 53 841 (



Summary

- The combination of far-infrared and capacitance spectroscopy allows for a detailed investigation of the many–particle states in InAs quantum dots.

- The shell structure of the electron states reveals itself in a non-monotonous Coulomb blockade.

- The far-infrared response is strongly affected by the electron–electron interaction, which allows for spectroscopy of a "Dot Periodic Table".

- The charging and the collective response of dot ensembles is influenced by lateral and vertical Coulomb coupling.