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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.998d - 30

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

"FIR Spectroscopy of Quantum Dots and Wires"

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

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Dr. Heitmann

TRIESTE, AUGUST 1997

FIR SPECTROSCOPY OF QUANTUM DOTS AND WIRES

BREAKING KOHN'S THEOREM

with

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University of Iceland, Reykjavik

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K. Eberl, K. Ploog

Max-Planck-Institut, Stuttgart

Happy Birthday

Vor 25 Jahren wurde der erste Mikroprozessor erfunden – und veränderte die Computer-Welt

Was haben der Mikroprozessor und die Imbißkette McDonalds gemeinsam? Beide feiern in diesem Jahr 25jährigen Geburtstag. Und beide haben in diesem Vierteljahrhundert die Welt radikal verändert. Happy Birthday!

Ted Hoff, Entwickler bei Intel, hielt sich 1971 nicht an seinen Auftrag und erfand den Mikroprozessor.

Am 15. November 1971 erschien in der amerikanischen Zeitschrift „Electronic News" die Geburtsanzeige für den ersten Mikroprozessor der Welt, den 4004. „Ein neues Zeitalter der integrierten Schaltung beginnt", titelte Erfinder Intel damals. Den Ingenieuren des drei Jahre zuvor gegründeten Halbleiter-Herstellers war es gelungen, auf einem einzigen Element („Chip") Recheneinheit, Befehlsdecoder sowie Ein- und Ausgabe-Baustein zusammenzufassen. Die „Central Processing Unit" (CPU) war geboren. Vorher gab es nur getrennte Bausteine, die erst auf Leiterplatten miteinander verbunden wurden.

Allerdings hatten die Ingenieure 1971 wohl noch keine Vorstellung davon, wie radikal die Umwälzungen durch den neuen Mikroprozessor werden würden. Kaum ein

Foto: Intel

Der Pentium-Prozessor: Er ist nur noch so groß wie ein Daumennagel.

Gerät, in dem die kleinen Alleskönner heute nicht vertreten sind: vom Musikchip in der Glückwunschkarte über Spielzeug und Waschmaschine bis hin zum Space Shuttle.

Dabei hatten die Väter des Mikrocomputers eigentlich etwas ganz anderes im Kopf gehabt. Der japanische Büromaschinen-Hersteller Busicom hatte Intel beauftragt, einen zwölfteiligen Chipsatz für eine programmierbare Rechenmaschine zu entwerfen. Verantwortlich dafür war Ted Hoff in der Entwicklungsabteilung.

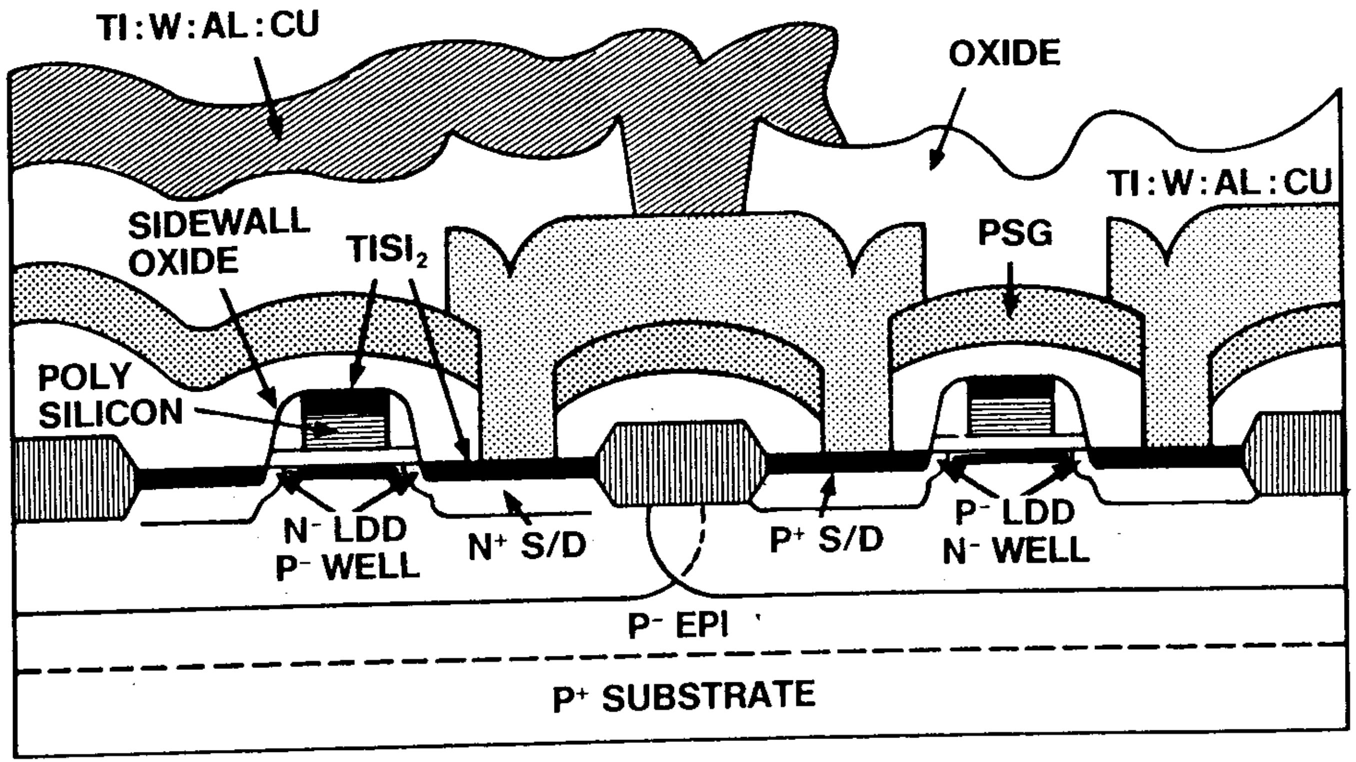
Aber der junge Ingenieur wollte sich nicht an die Vorgaben von Busicom halten. Er war sich sicher, daß die Aufgabe mit einem einzigen programmierbaren Allround-Chip zu lösen sein müßte. Genau neun Monate ent-

Der von Er le Sieg des zess

aus dem Jahr 194[illegible] 18000 Röhren füll[illegible] einen ganzen Raum den mit Starkstrom [illegible]

Ganze 60000 Doll[illegible] Intel für die Entwic[illegible] Hoff und sein Tea[illegible] entsetzt, als sie erfu[illegible] nicht nur die fertig[illegible] sondern auch die R[illegible] Design verkauft wo[illegible] ren. Denn sie w[illegible]

EPIC™ Prozeß



Der EPIC™-Prozeß wird für die Herstellung von ACL-Bausteinen herangezogen (ACL = Advanced CMOS Logic). Er zeigt viele Vorteile:

- Bewährte DRAM-Prozeß-Technologie für Massenproduktion
- 1,0 μ effektive Gatelänge für sub-ns interne Laufzeiten
- P/P + Epitaxie Substrat zur Latch-up-Unterdrückung
- Twin-well-Struktur für hohe Packungsdichte der zukünftigen LSI/VLSI-Produkte
- Titansilicid zur Verminderung interner Bahnwiderstände ergibt minimale Verzögerungszeit
- Kupfer-dotiertes Aluminium auf TI/W zur Vermeidung von Elektromigration und für bessere Gesamtzuverlässigkeit
- Sidewall Oxide-Prozeß ergibt sowohl kleinste Gate-Source/Gate-Drain-Kapazitäten für maximale Geschwindigkeit als auch die LDD-Struktur für die Unterdrückung der „hot-carrier" → verbesserte Zuverlässigkeit

EPIC = Enhanced Performance Implanted CMOS

TM = Trademark of Texas Instruments Incorporated

[illegible]

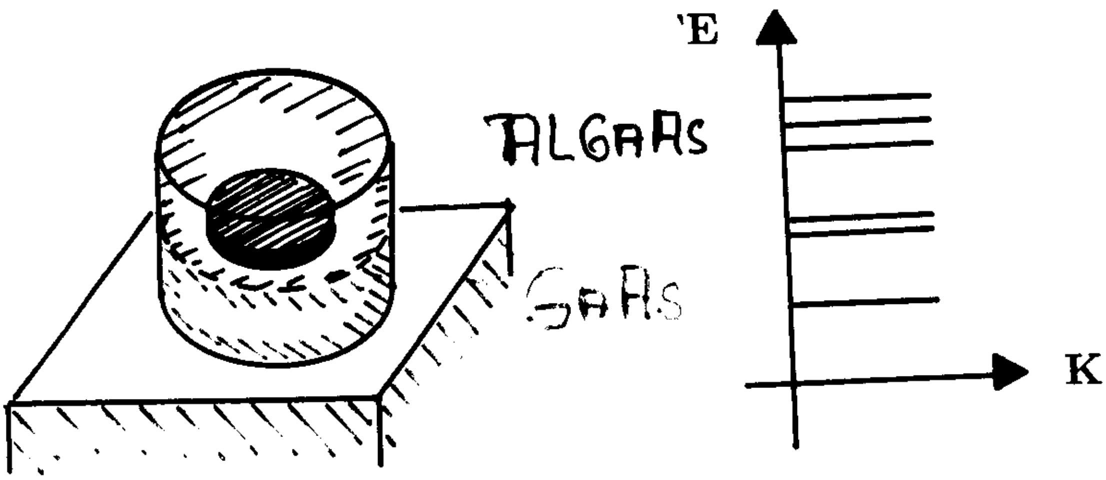
Year of first DRAM shipment	1995	1998	2001	2004	2007	2010
Minimum feature (μm)	0.35	0.25	0.18	0.13	0.10	0.07
Memory • bits/chip (DRAM/Flash)	64M	256M	1G	4G	16G	64G
• cost/bit @volume (millicents)	0.017	0.007	0.003	0.001	0.0005	0.0002
Logic (High Volume: Microprocessor) • logic transistor/cm² (packed) • bits/cm² (cache SRAM) • cost/transistor @volume (mc)	4M 2M 1	7M 6M 0.5	12M 20M 0.2	25M 50M 0.1	50M 100M 0.05	90M 300M 0.02
Logic (Low Volume: ASIC) • transistors/cm² (auto layout) • non-recurring engineering cost/transistor (millicents)	2M 0.3	4M 0.1	7M 0.05	12M 0.03	25M 0.02	40M 0.01

QUANTUM CONFINED MICROSTRUCTURED SEMICONDUCTOR SYSTEMS

2D: QUANTUM WELLS, HETEROSTRUCTURES

1D: QUANTUM WIRES

<u>0D: QUANTUM DOTS</u>



<u>DISCRETE ENERGY LEVELS</u>

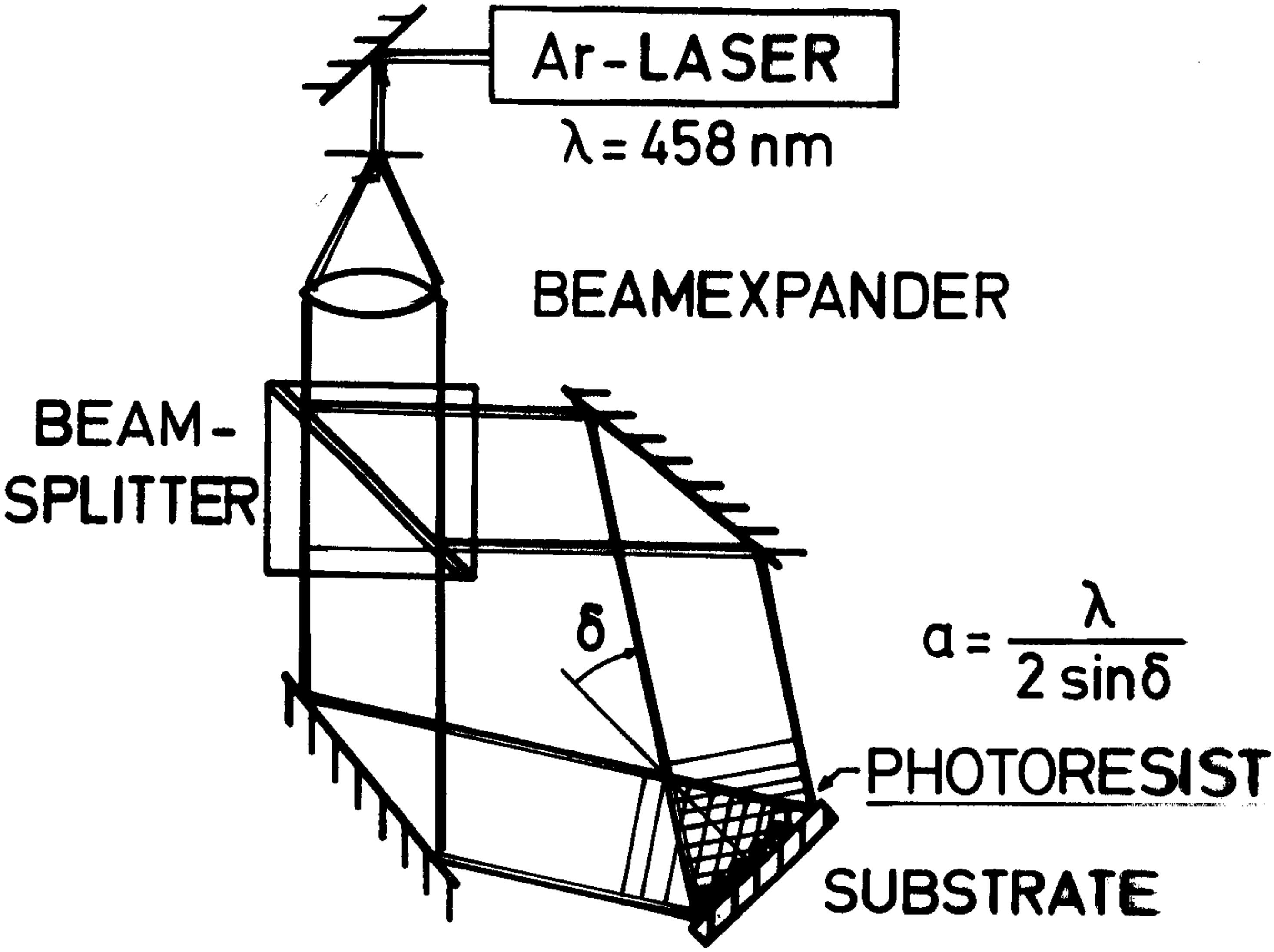
<u>" QUANTUM-DOT ATOMS"</u>

LIMITS ?

e^-

Holographic Lithography

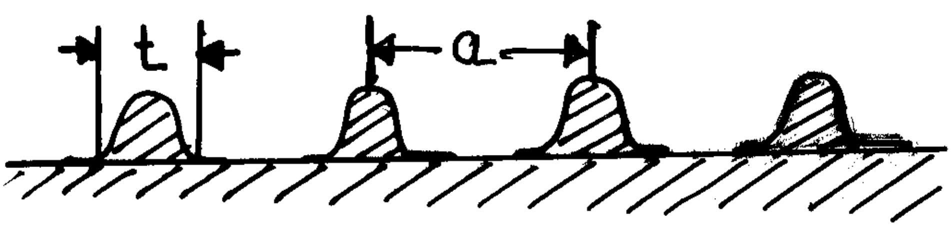
fabrication of photoresist gratings with small periodicities on the top of the sample



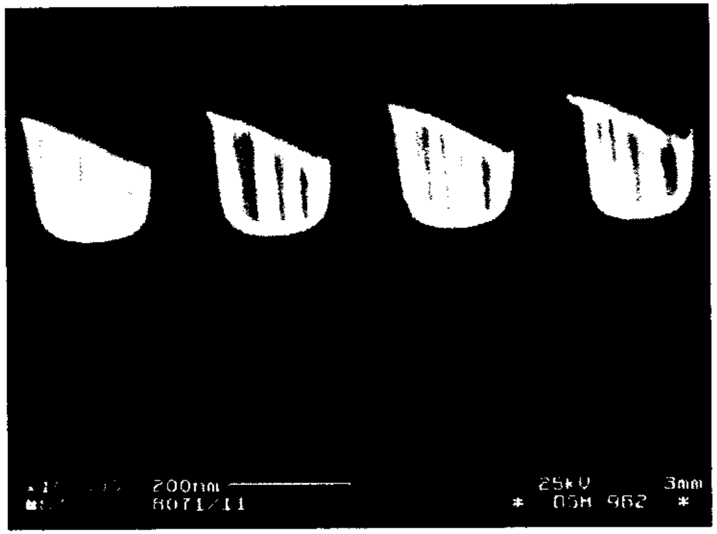
periodicity: $a = \frac{\lambda}{2 sin\delta}$

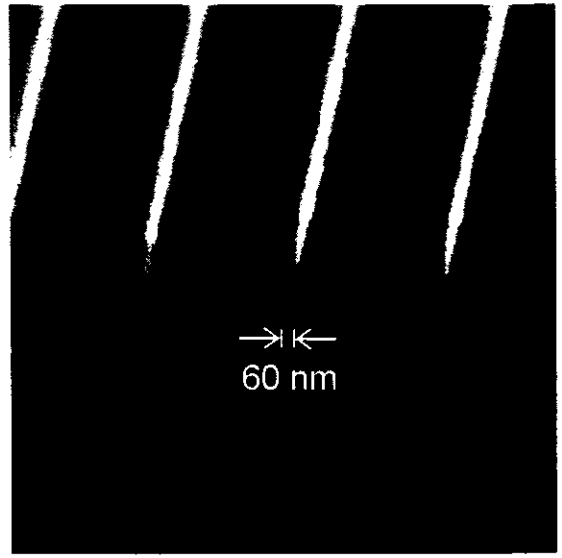
$\lambda = 458nm \quad \Rightarrow \quad a = 230nm$

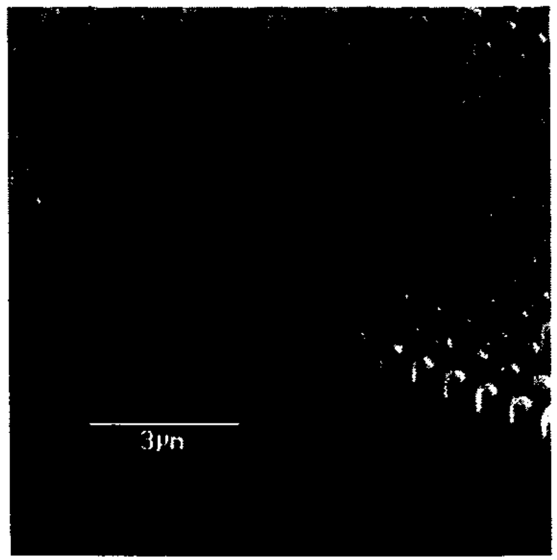
$n = 1.5 \quad \Rightarrow \quad a = 160nm$



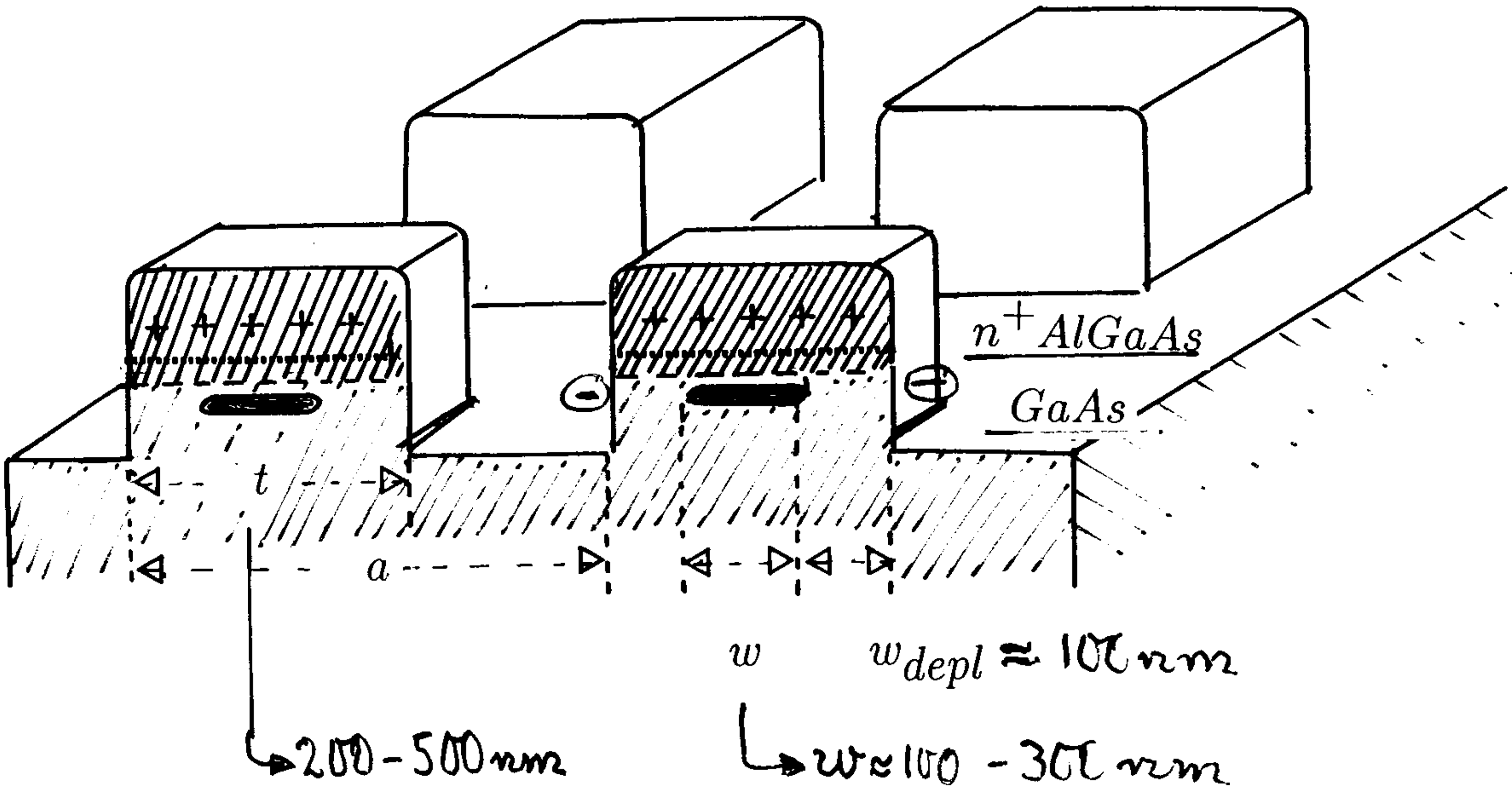
SEM pictures of deep-etched structures



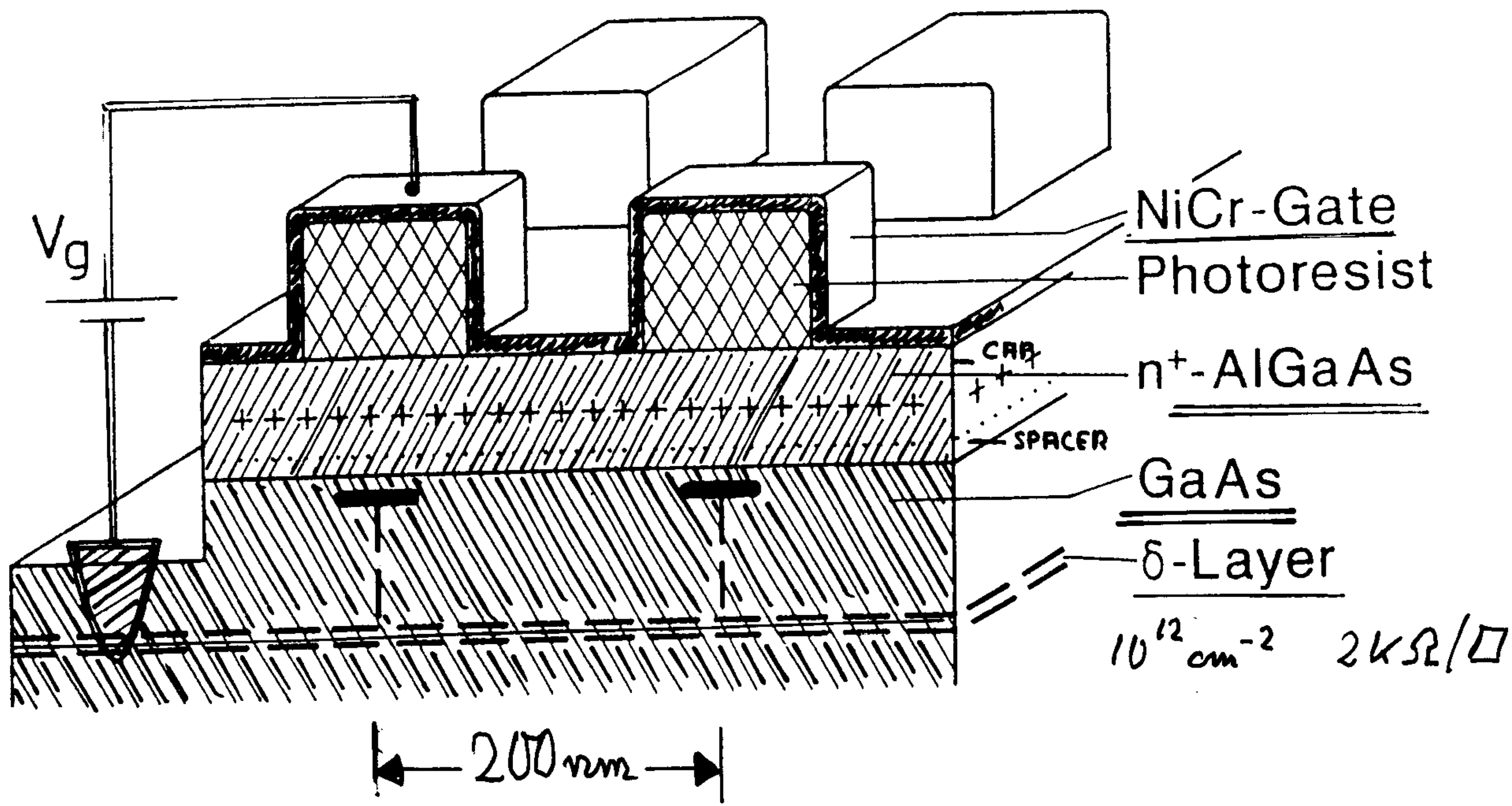




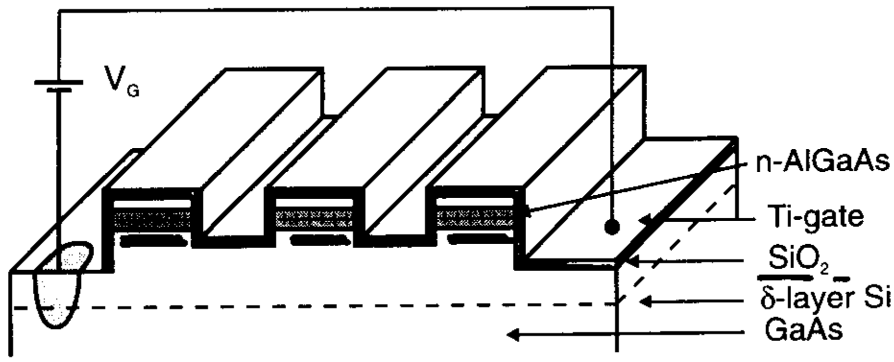
DEEP-MESA-ETCHED QUANTUM DOTS

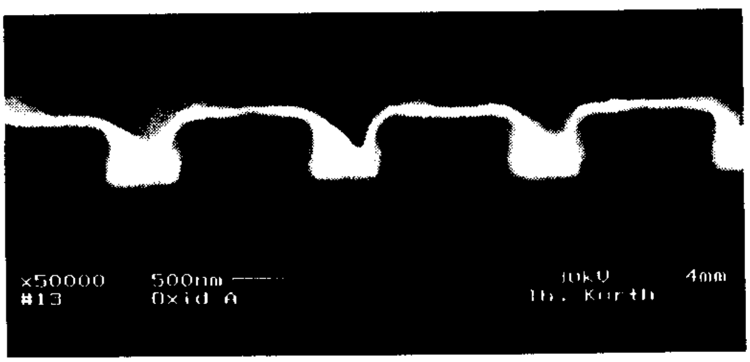


FIELD-EFFECT CONFINED QUANTUM DOTS

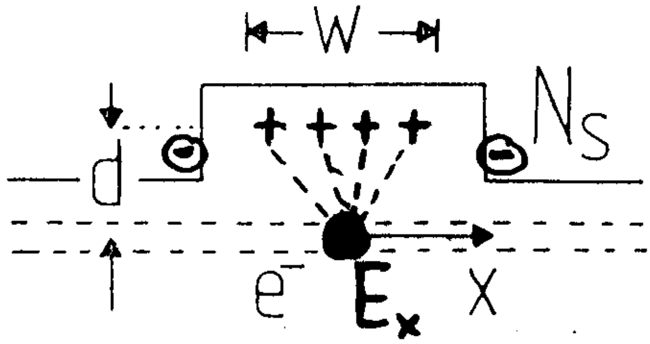


DEEP-MESA-ETCHED QUANTUM WIRES WITH TOP- AND SIDEGATE



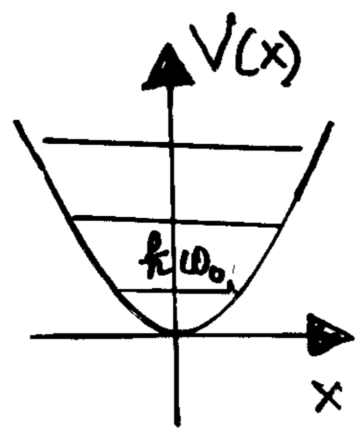


CONFINEMENT
IN ETCHED MICROSTRUCTURES



$$\vec{F_x} = e\vec{E_x} \propto x$$

$$V(x) = \frac{1}{2} m^* \omega_0^2 x^2$$



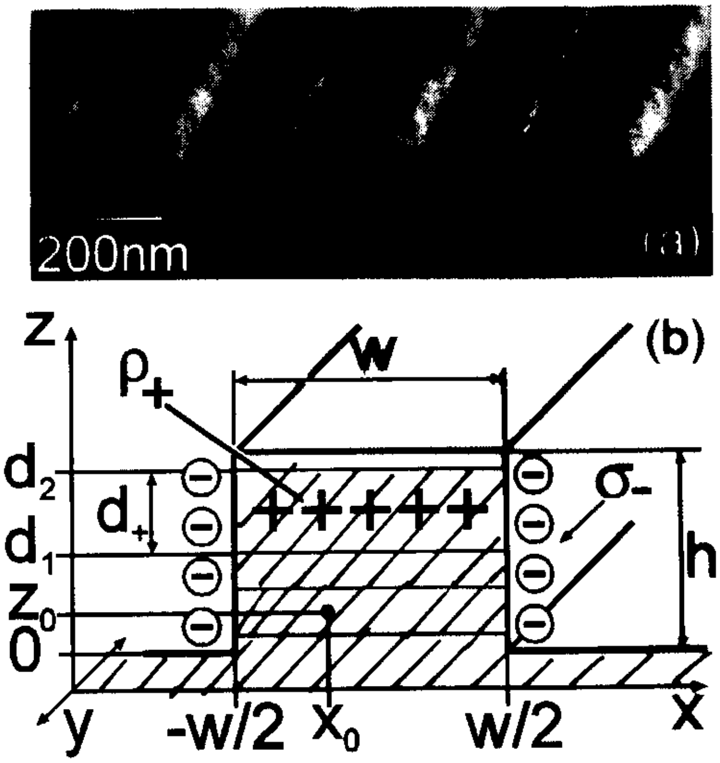
PARABOLIC CONFINEMENT

$$\omega_0^2 \approx \frac{N_S e^2}{2\pi\epsilon_{eff}\epsilon_0 m^*} \frac{w}{w^2 + d^2}$$

EIGENFREQUENCY

EXTERNAL POTENTIAL

MODEL CALCULATIONS FOR DEEP-MESA-ETCHED QUANTUM WIRES

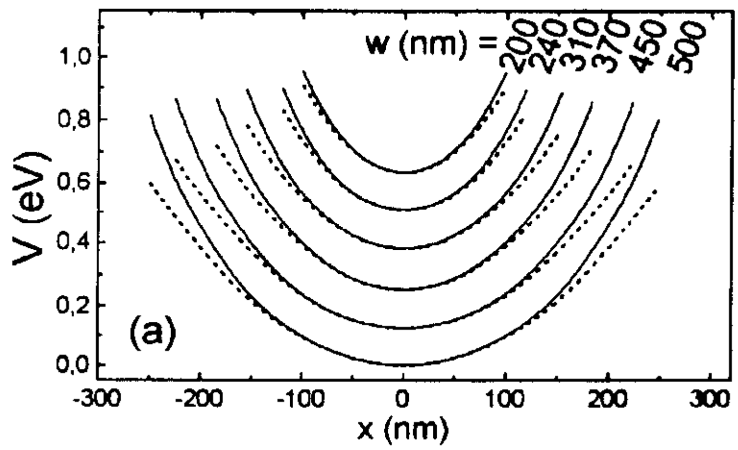


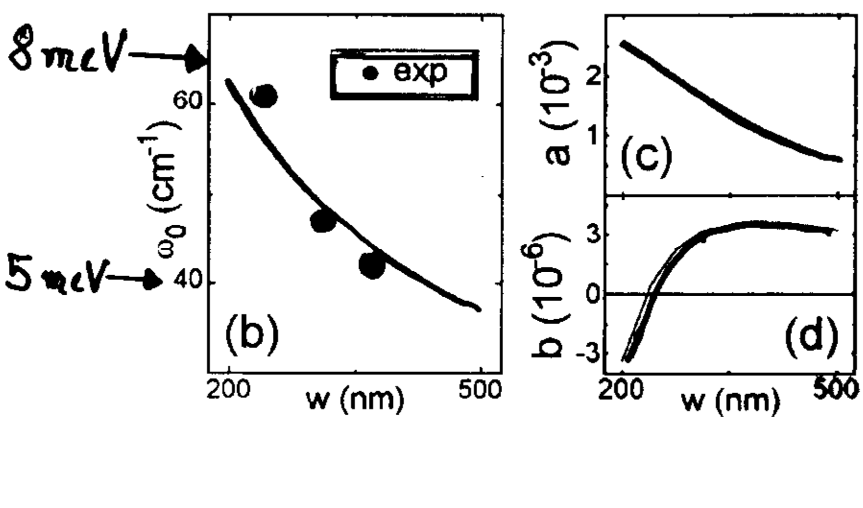
S. Riege et al APL 70, 111 (97)

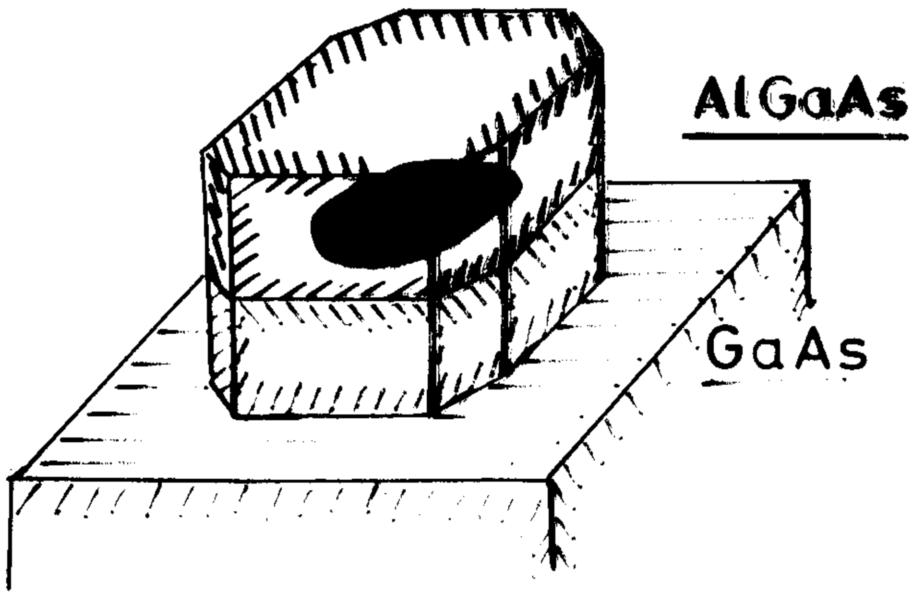
ELECTROSTATIC CALCULATION OF THE EXTERNAL POTENTIAL

APPROXIMATION BY A POTENTIAL:

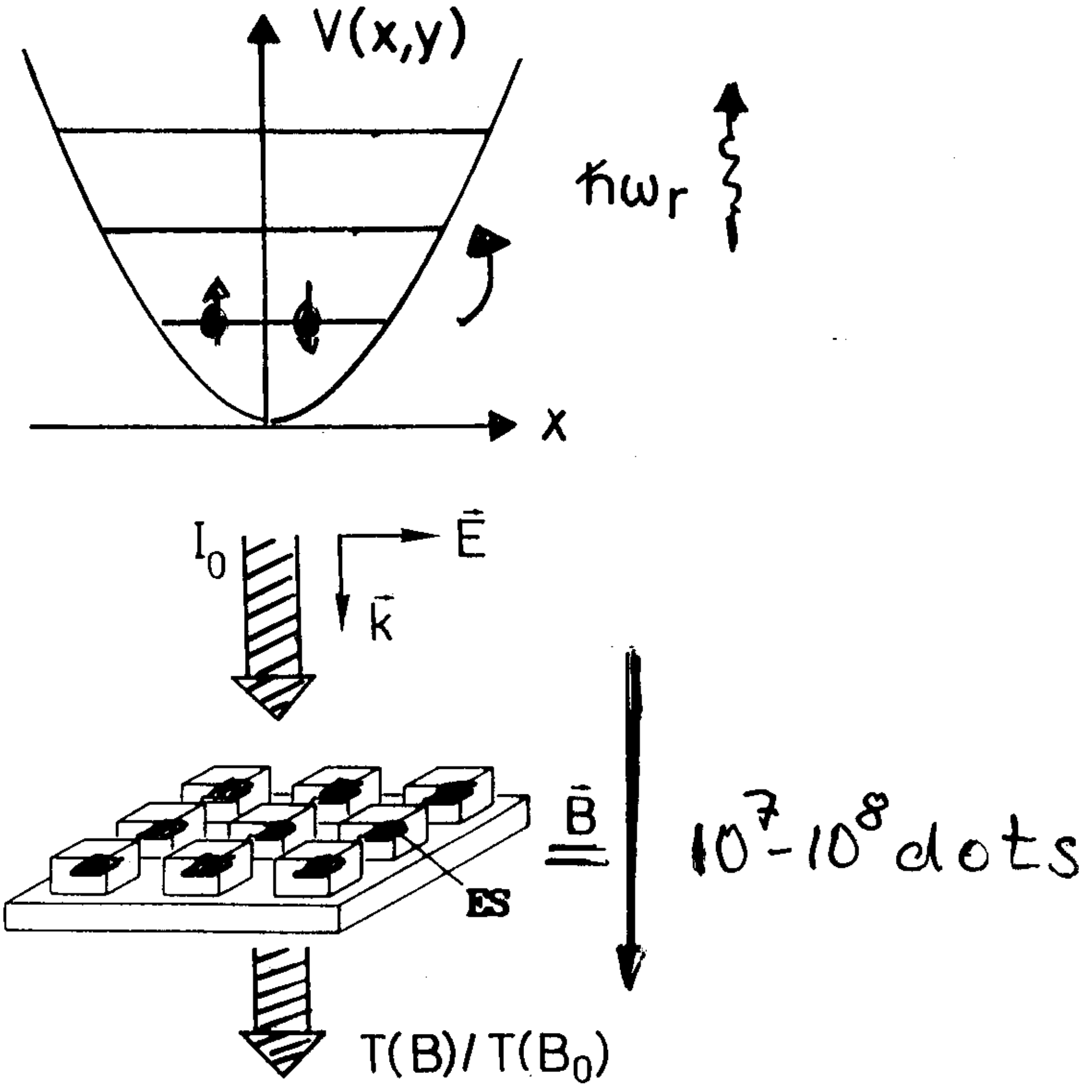
$$V(x) = \frac{1}{2}\hbar\omega_0 \left(\left(\frac{x}{l_0}\right)^2 + a\left(\frac{x}{l_0}\right)^4 + b\left(\frac{x}{l_0}\right)^6 \right)$$



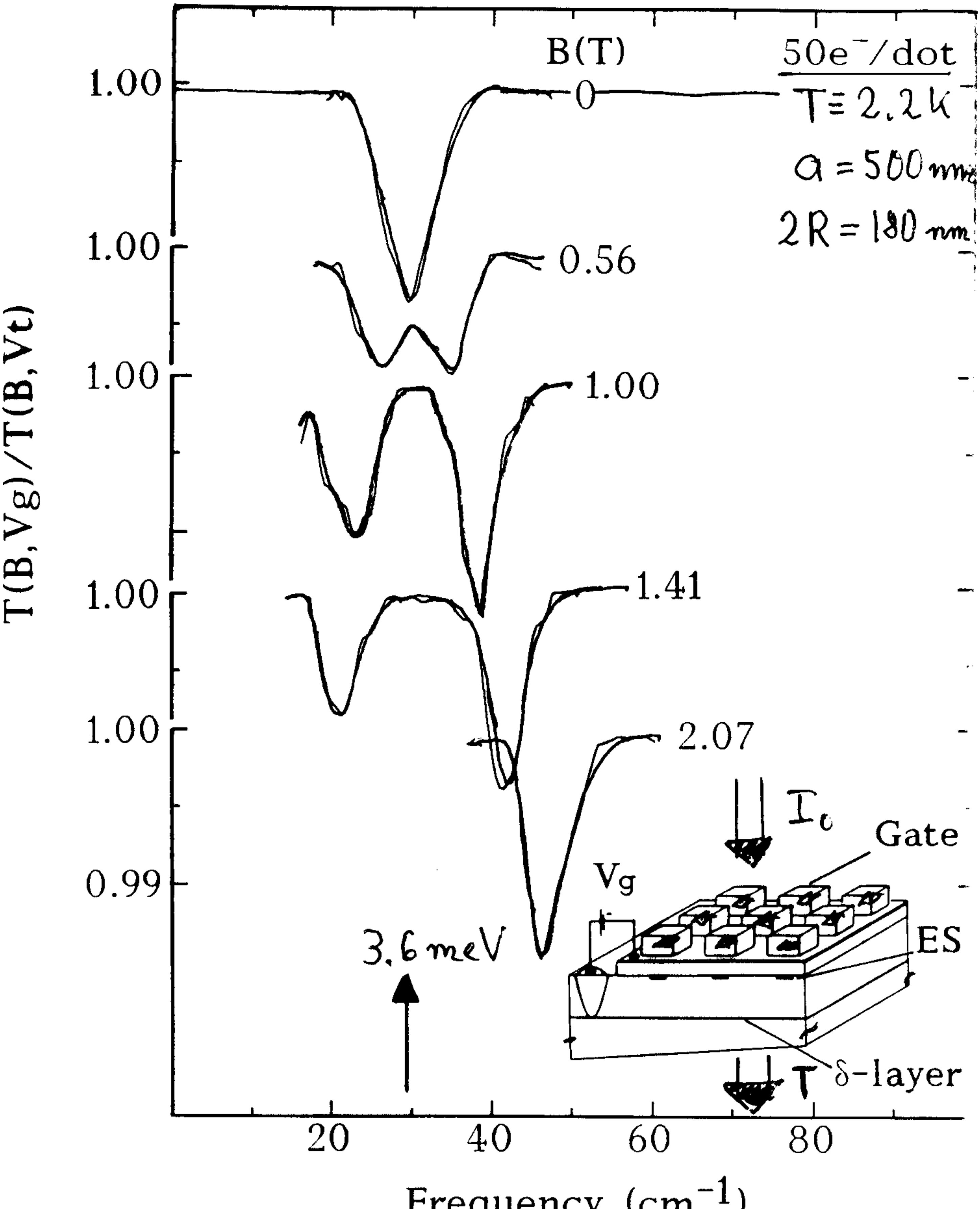




FIR SPECTROSCOPY

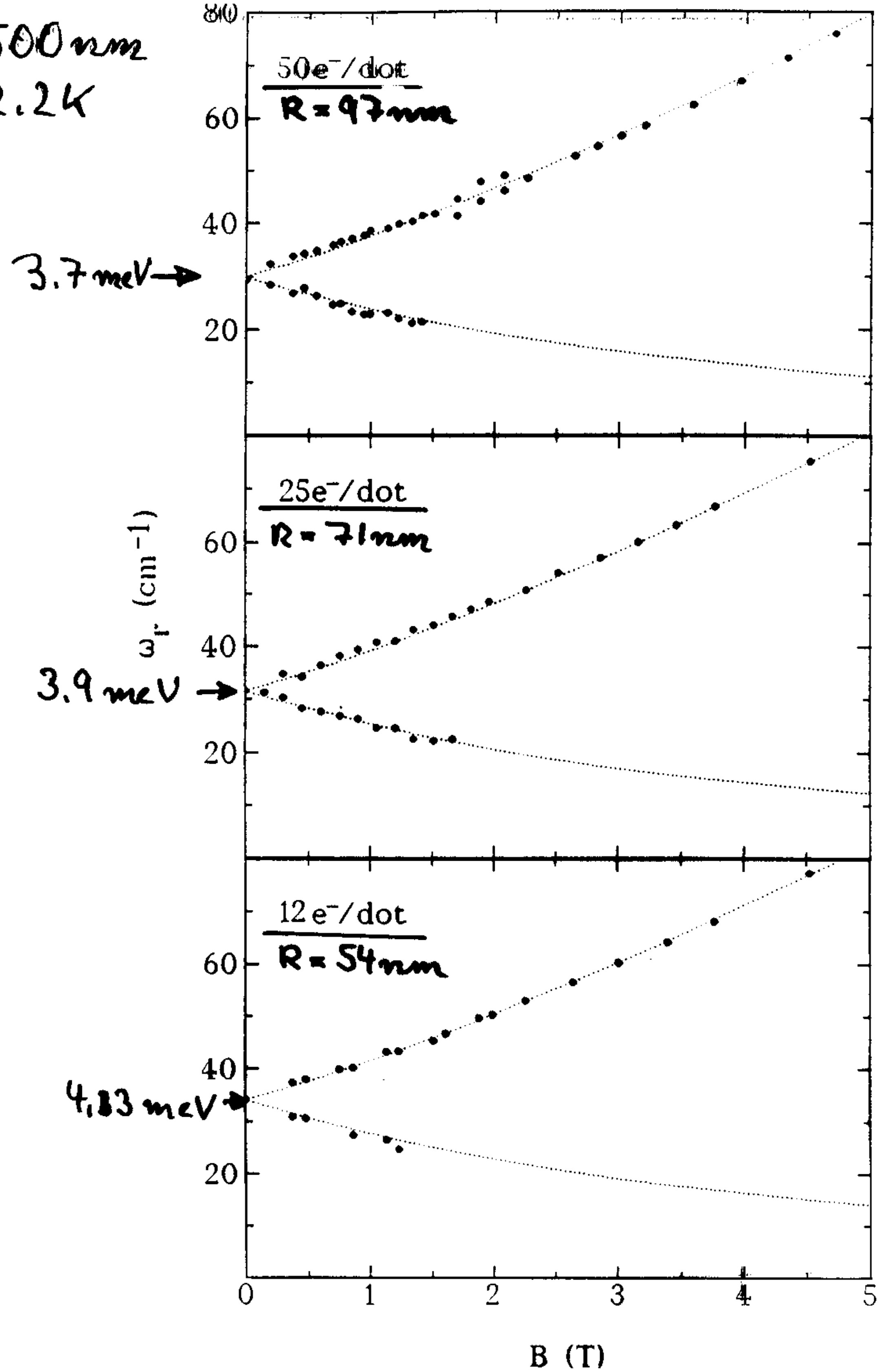


FIR RESPONSE OF FIELD-EFFECT CONFINED QUANTUM DOTS IN A MAGNETIC FIELD



B-DISPERSION OF THE RESONANCE FREQUENCY IN FIELD-EFFECT CONFINED QUANTUM DOTS

a = 500 nm
T = 2.2 K



3D: Allen et al
InSb Sikorsky + Hewlett

ATOM-LIKE BEHAVIOR: SINGLE-PARTICLE ASPECTS

ONE ELECTRON IN A PARABOLIC CONFINEMENT

B

$$H(\vec{r}, \vec{p}) = \frac{1}{2m^*}[\vec{p} + \frac{e}{c}\vec{A}(\vec{r})]^2 + \frac{1}{2}m^*\Omega_0^2 r^2$$

Ω_0 = confinement energy

SOLUTION

$\omega_c = \frac{e \cdot B}{m^*}$

$$E_{n,\ell} = \ell \cdot \frac{\hbar\omega_c}{2} + (2n + |\ell| + 1) \cdot \sqrt{(\hbar\Omega_0)^2 + \frac{(\hbar\omega_c)^2}{4}}$$

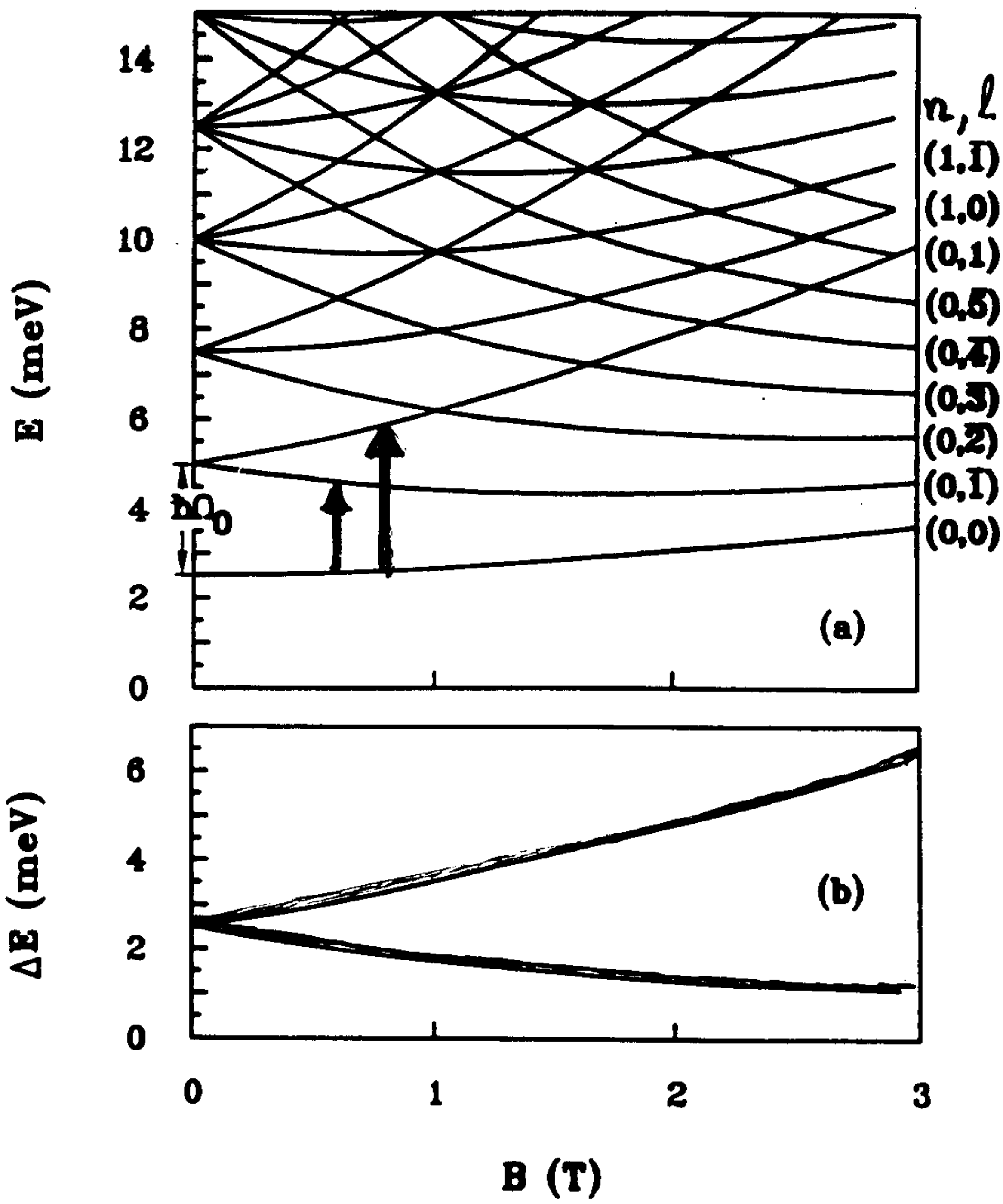
$n = 0, 1, 2, 3..$ radial quantum number

$\ell = 0, \pm 1, \pm 2, \pm 3, ...$ azimuthal quantum number

Fock, Z. Physik 1928.

SINGLE-PARTICLE SPECTRUM OF A 2D HARMONIC OSCILLATOR IN A MAGNETIC FIELD

ONE ELECTRON !



Para-He Ortho-He

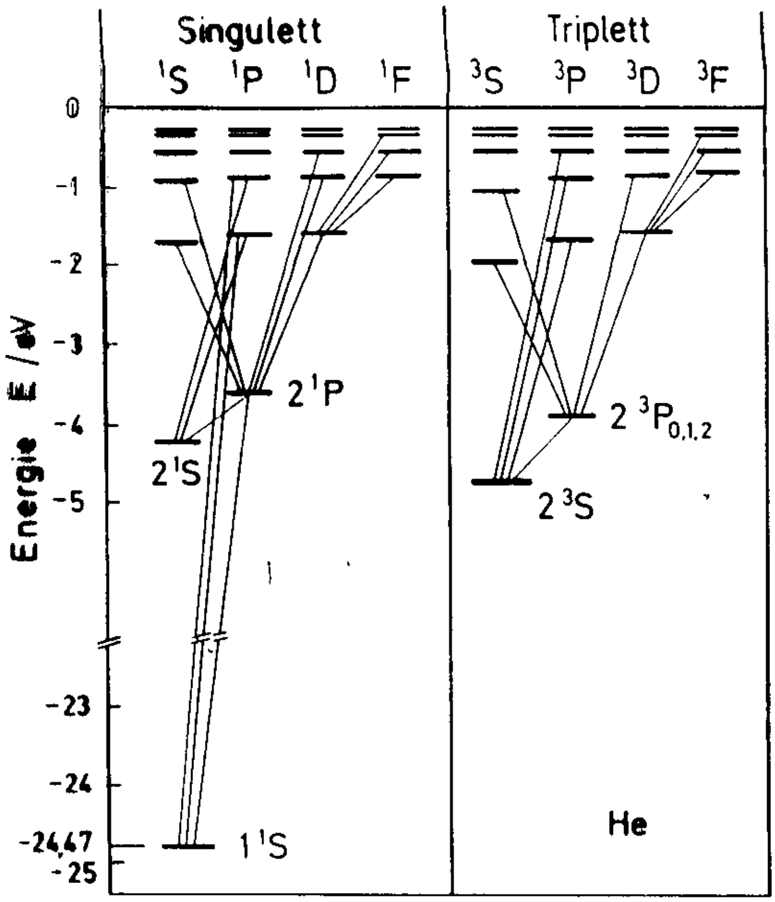


Abb. 17.1. Termschema des He-Atoms. Einige der erlaubten Übergänge sind eingezeichnet. Es gibt zwei Termsysteme, zwischen denen strahlende Übergänge verboten sind, das Singulett- und das Triplett-System. Die Übergänge im Singulett-System überspannen einen Energiebereich von 25 eV, die im Triplett-System nur 5 eV

$|1,2\rangle$, $\psi_1 \cdot \psi_2$

TWO-PARTICLE-WAVE FUNCTIONS AND EIGENVALUES

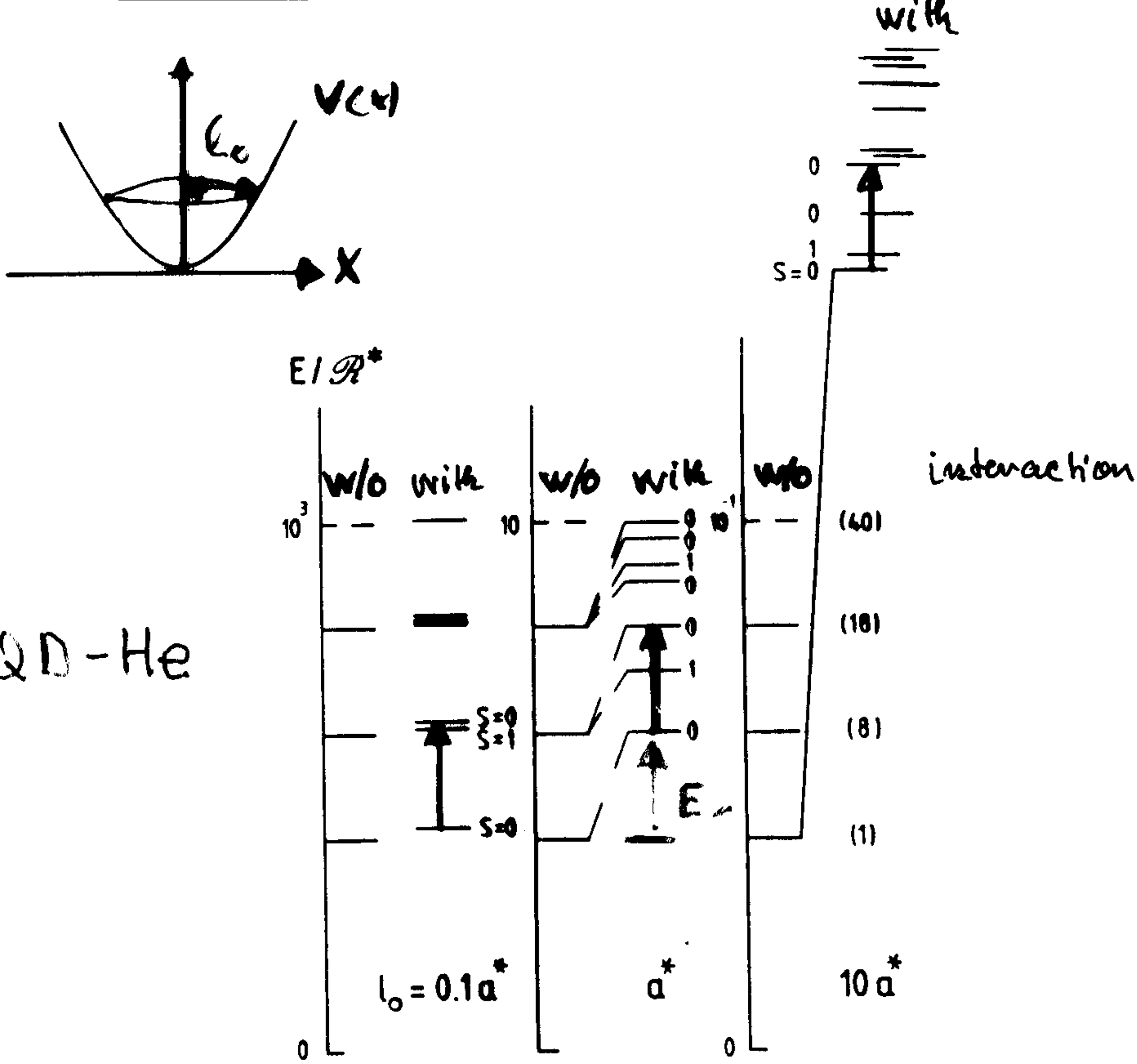
Excitation Spectrum

of

Coulomb-He

ENERGY SPECTRA OF QUANTUM-DOT ATOMS = QD - He

$2e^-$, box potential, Bryant, PRL59, 1140 (1987)
$3-5e^-$, parab. potential, Maksym and Chakraborty, PRL65, 108 (1990)
$2e^-$, parab. potential, Merkt et al, PRB 43, 7320 (1991)



Confinement: $E_q = \hbar^2/m^* l_0^2$ $\propto l^{-2}$

Coulomb: $E_c = e^2/\epsilon l_0$ $\quad l^{-1}$

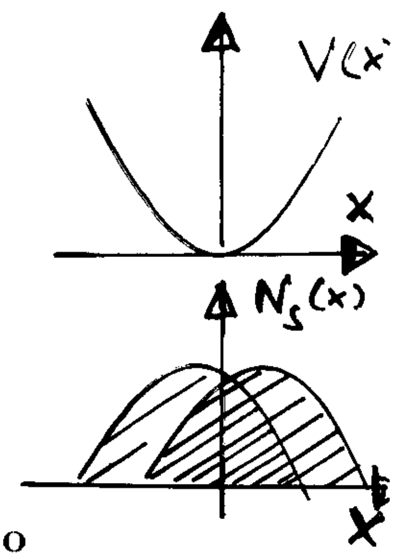
$l_0 = 18nm : E_q = 3.4meV \quad E_c = 6.5meV$

Effective Bohr radius in GaAs $a_0^* = 11nm$:

N ELECTRONS
IN A PARABOLIC POTENTIAL
ELECTRON-ELECTRON INTERACTION

SEPARATION
INTO CENTER-OF-MASS MOTION AND RELATIVE MOTION

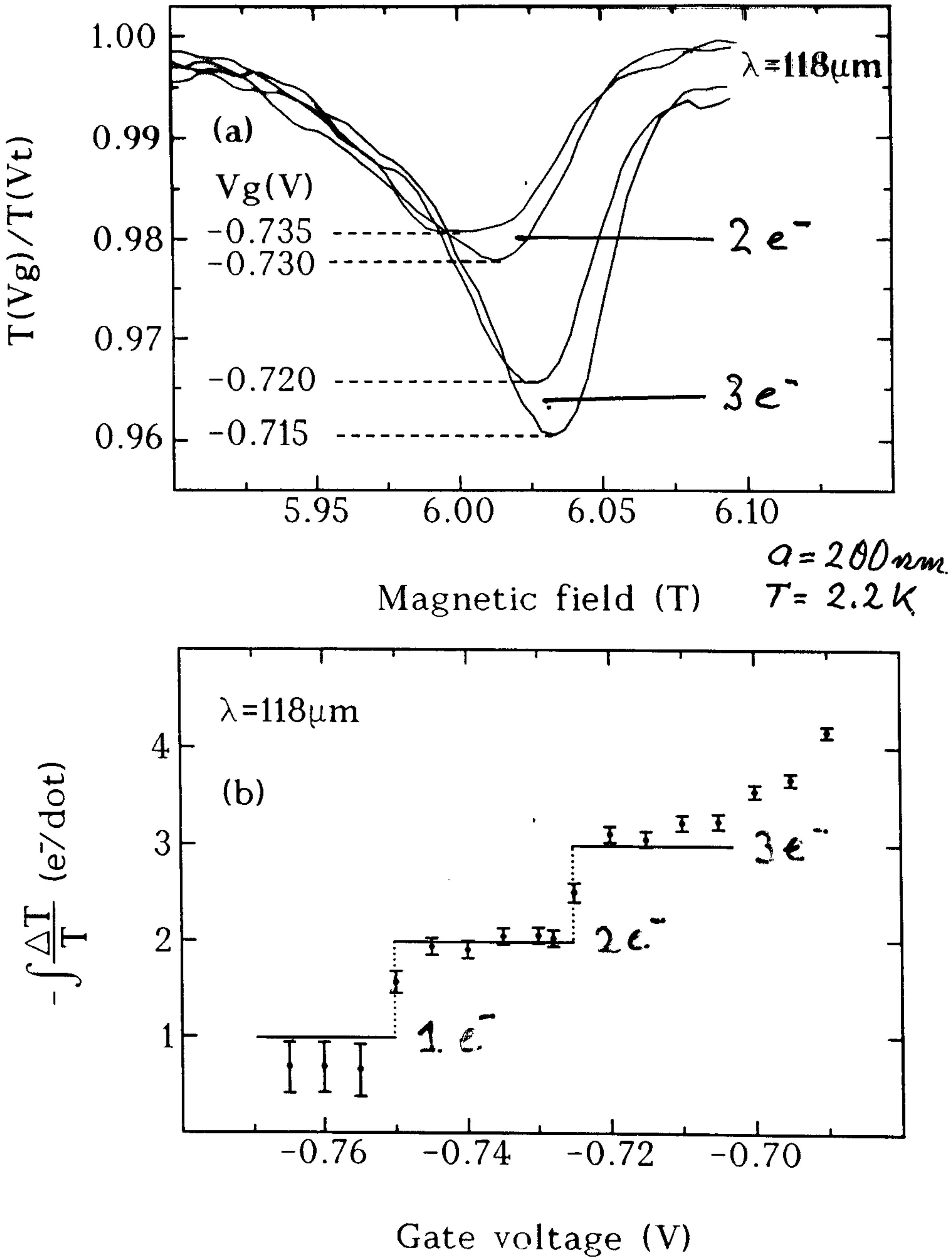
$$H_N = H(\vec{R}, \vec{P}) + H_{rel}(\vec{r}_{j,rel}, \vec{p}_{j,rel})$$



Dipole excitation couples only to center-of-mass motion
Rigid motion of all electrons
Independent on number of electrons

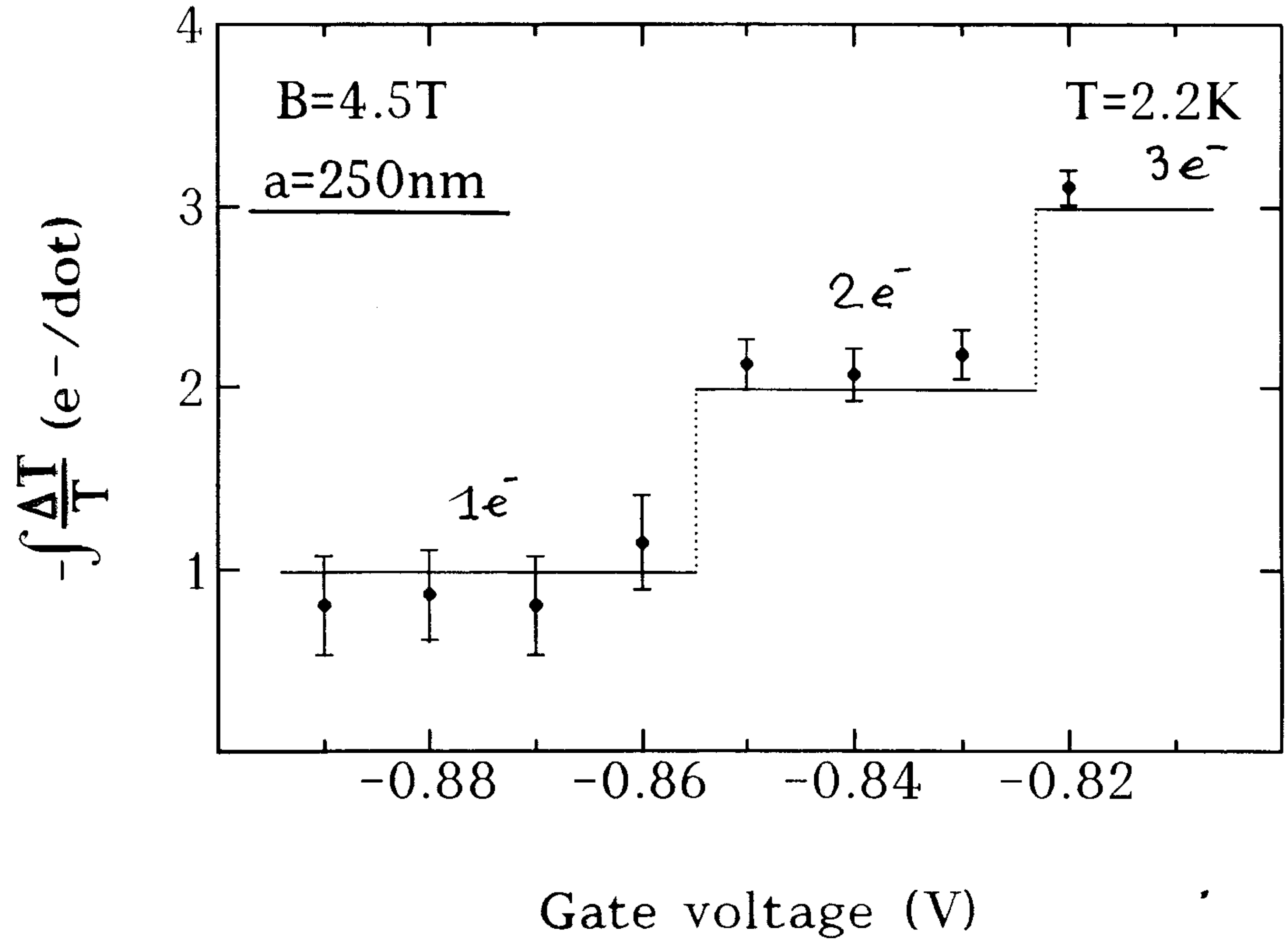
GENERALISATION OF KOHN'S THEOREM

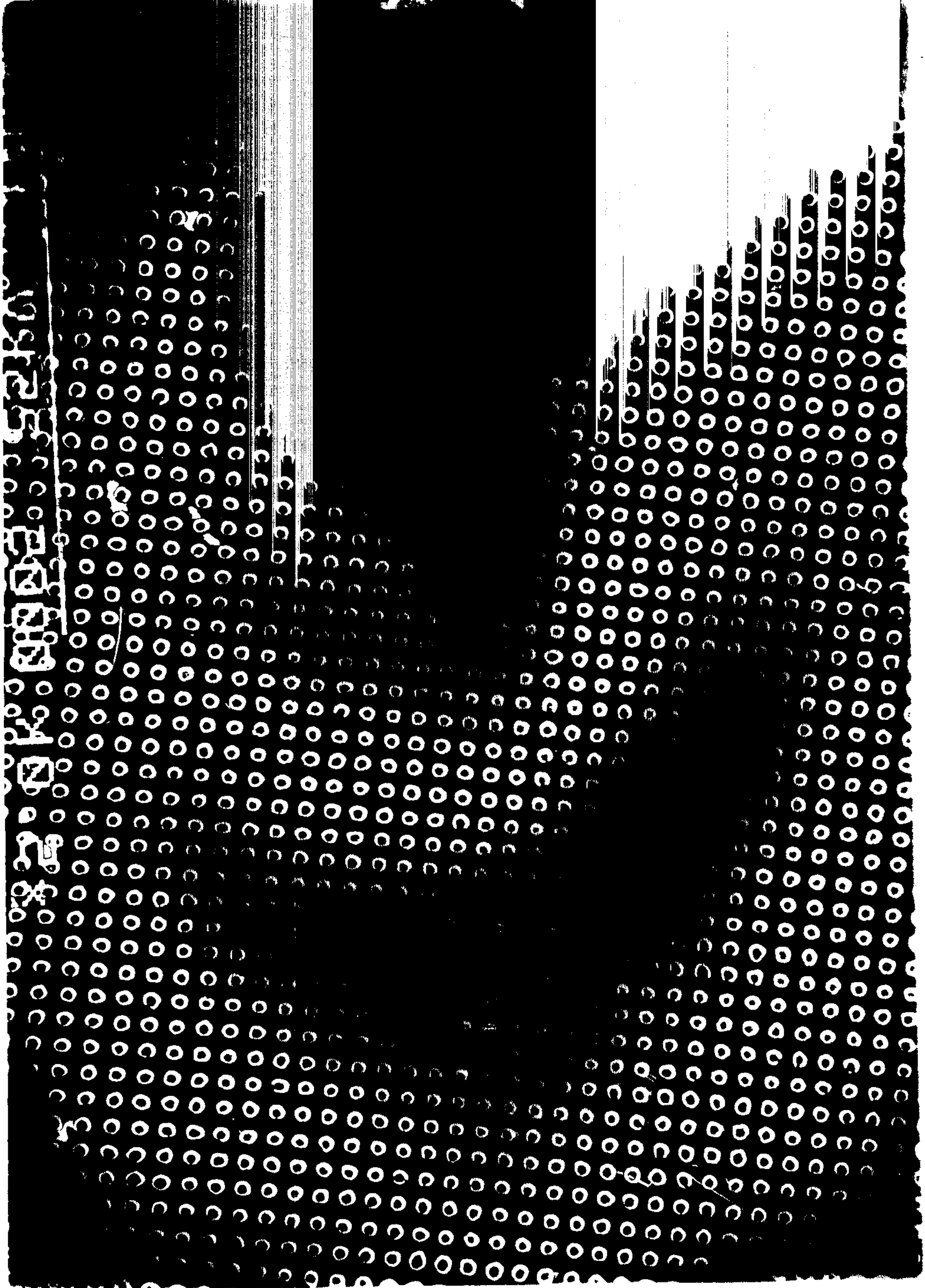
Brey, Johnson, Halperin - Maksym, Chakraborty (89)
Ruden, Döhler (93)


1.00
0.99
0.98
0.97
0.96
T(Vg)/T(Vt)
λ=118μm
(a)
Vg(V)
-0.735
-0.730
-0.720
-0.715
2 e⁻
3 e⁻
5.95
6.00
6.05
6.10
Magnetic field (T)
a = 200 nm
T = 2.2 K
λ=118μm
(b)
4
3
2
1
-∫ΔT/T (e⁻/dot)
3 e⁻
2 e⁻
1 e⁻
-0.76
-0.74
-0.72
-0.70
Gate voltage (V)

FIELD-EFFECT CONFINED QUANTUM DOTS

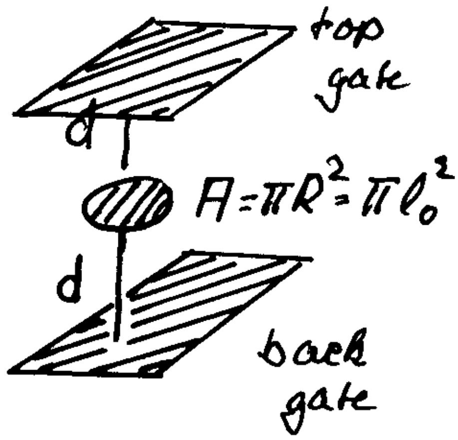
INTEGRATED FIR ABSORPTION STRENGTH





COULOMB EFFECTS

ESTIMATION OF C
GIVES



$$C = \frac{\epsilon\epsilon_0 \pi R^2}{d_{eff}}$$

$R = 27$ **nm from** l_0

$d_{eff} =$ **50nm**

$$C = 5.10^{-18}\ F$$

ENERGY REQUIRED TO CHARGE THIS CAPACITOR WITH ONE ELECTRON

$$E_c = \frac{e^2}{2C} = 15\text{meV}$$

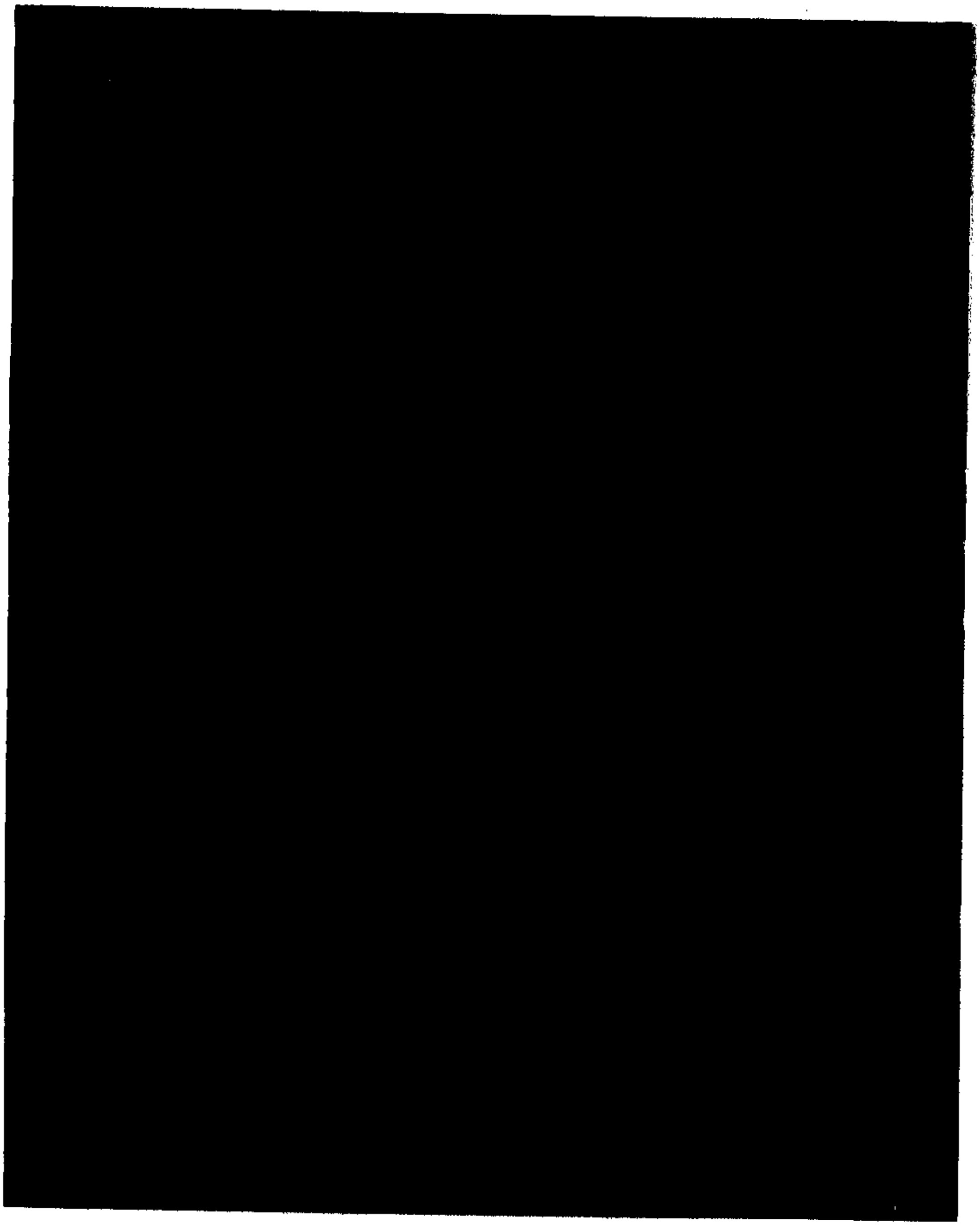
larger than kT
larger than local fluctuations
of threshold voltage
or dot geometry

STABILIZES A WELL DEFINED NUMBER OF ELECTRONS IN EACH DOT

Breaking Kohn's Theorem

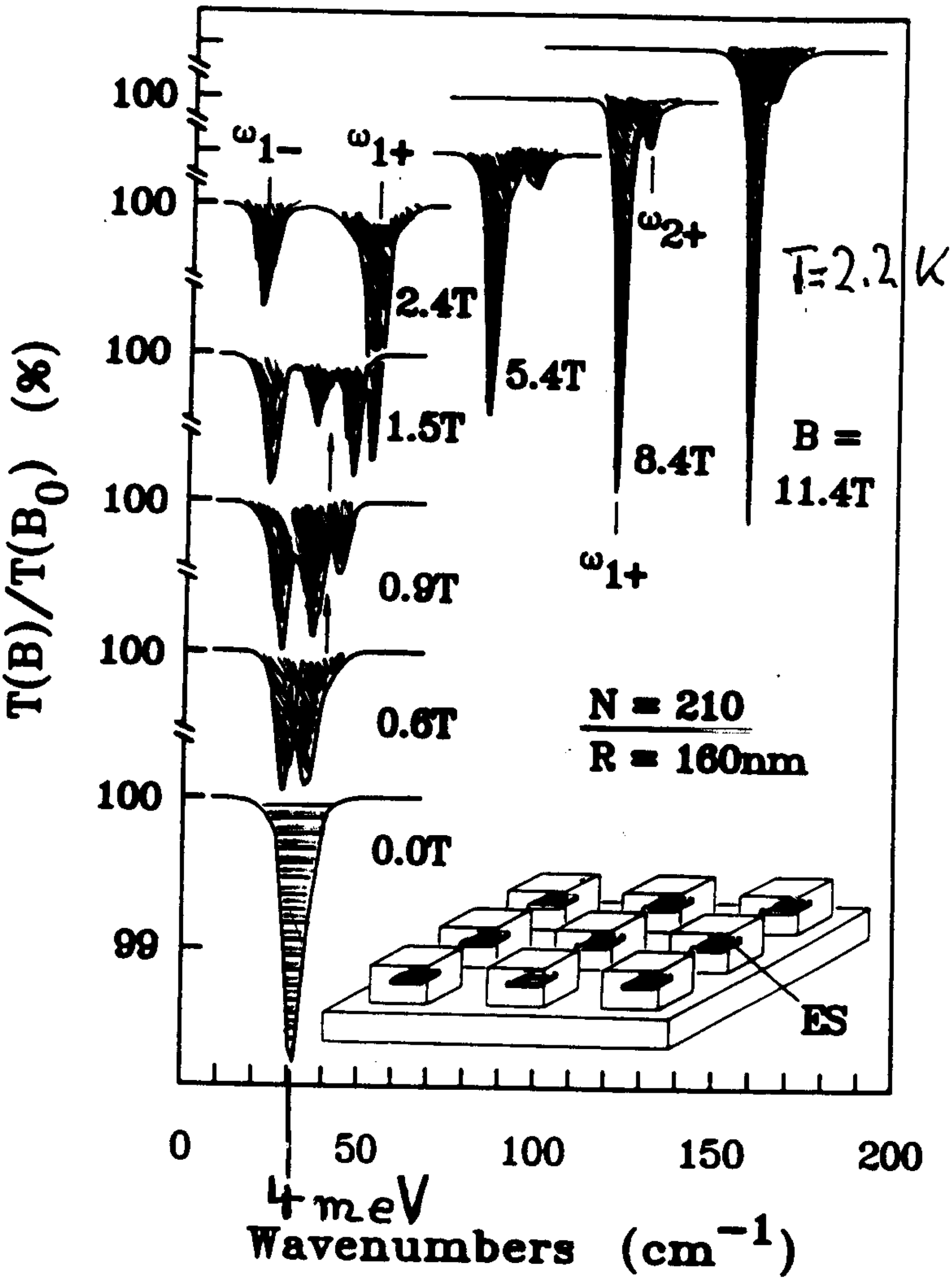
- Non-parabolic potential
- Non-parabolic band structure
- Tilted magnetic fields
- Non-dipole excitation
- Raman Experiments

DEEP-MESA ETCHED QUANTUM DOTS IN AlGaAs-GaAs



$500nm \cdot 500nm$ with rounded corners
lateral depletion $\approx 100nm$
one-particle separation $\approx 2meV$
estimated from wires prepared under identical conditions

FIR RESPONSE OF AlGaAs-GaAs QUANTUM DOTS IN A MAGNETIC FIELD B



N = 210 ELECTRONS PER DOT

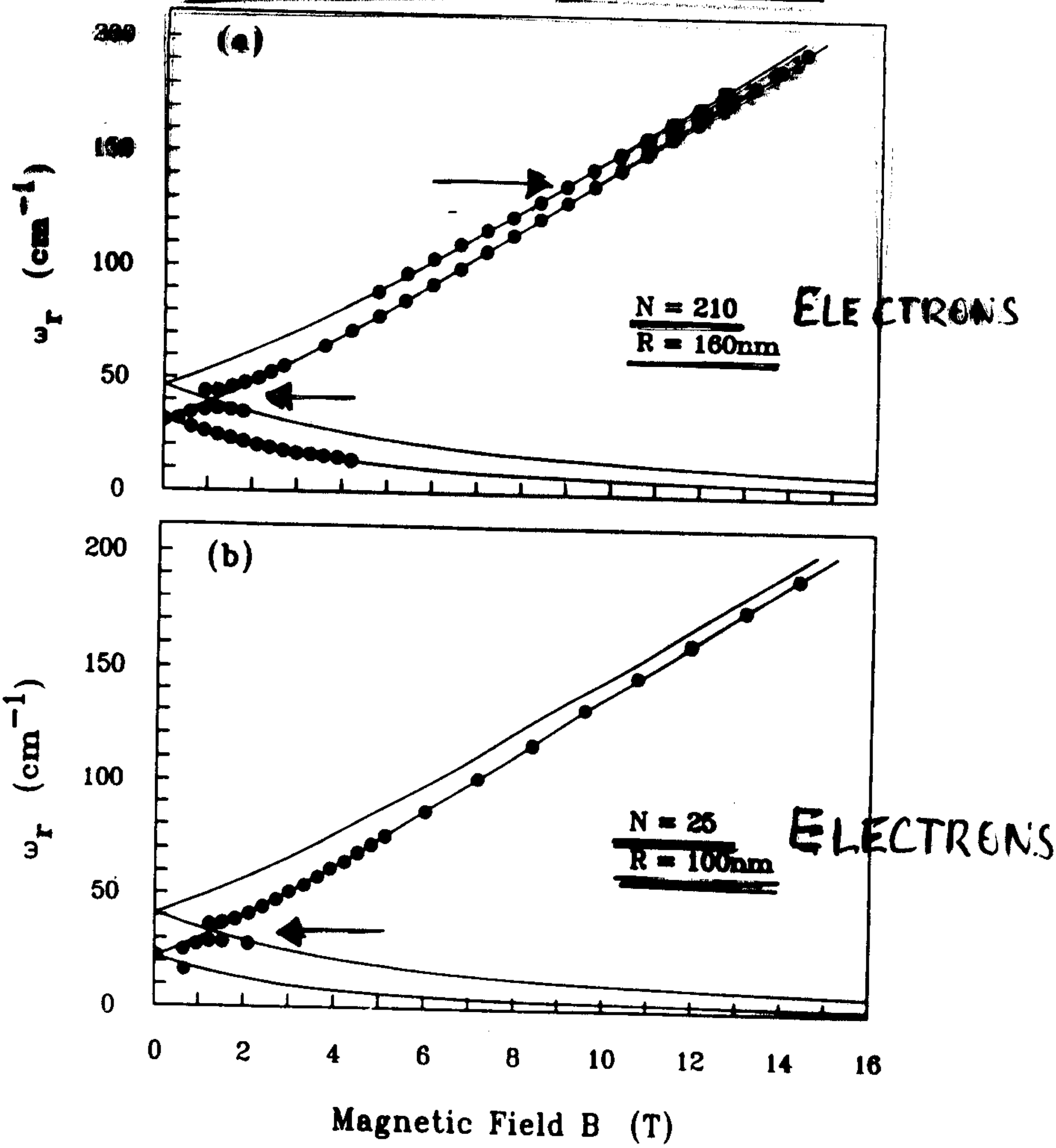
GEOMETRICAL RADIUS: 250 nm

ELECTRICAL RADIUS: 160 nm

SINGLE PARTICLE ENERGY: 2meV

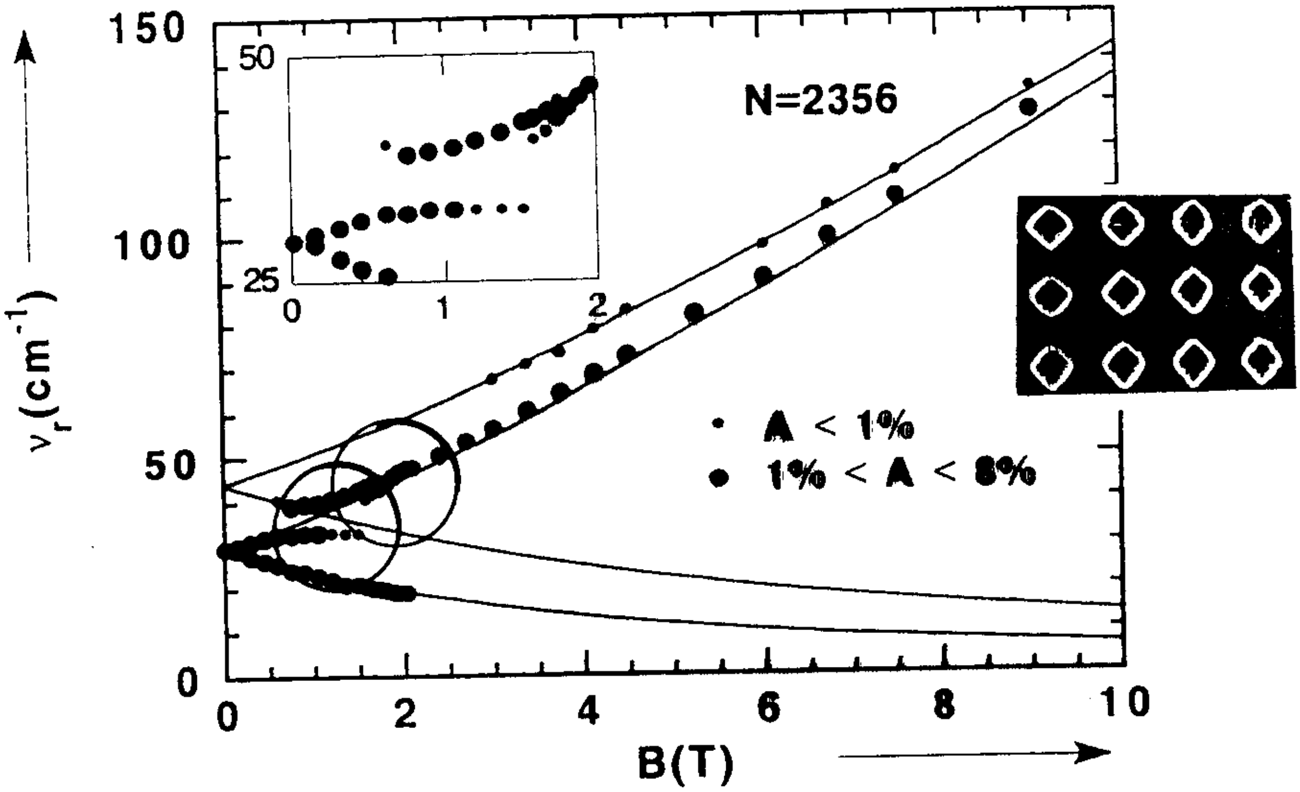
B-DISPERSION OF RESONANCE FREQUENCIES

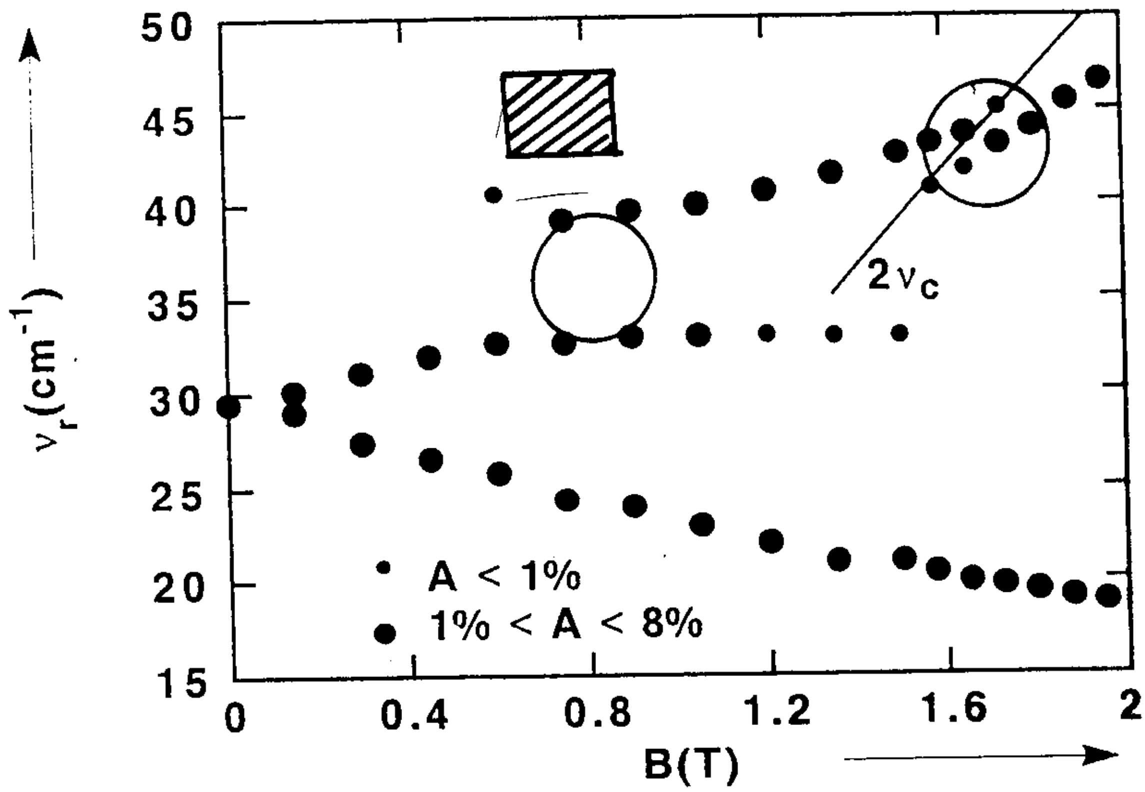
HIGHER MODES AND ANTI-CROSSING



IN DEEP-MESA-ETCHED QUANTUM DOTS

a=2000nm, 1000x1000 nm^2, N=2500 e$^-$/dot, R= 330nm



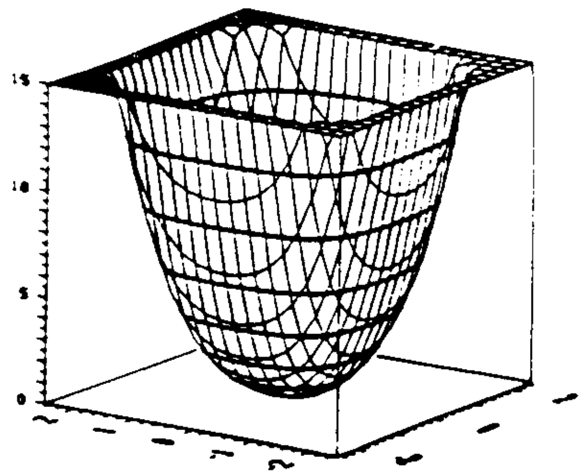


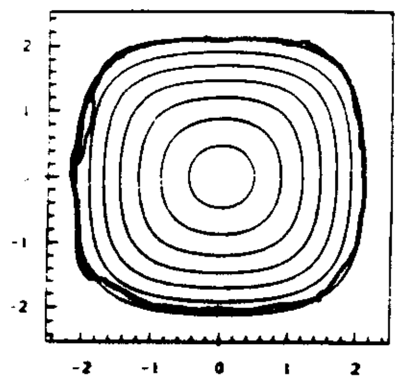
MODE SPLITTING FROM SQUARE■-SHAPED NON-PARABOLICITY

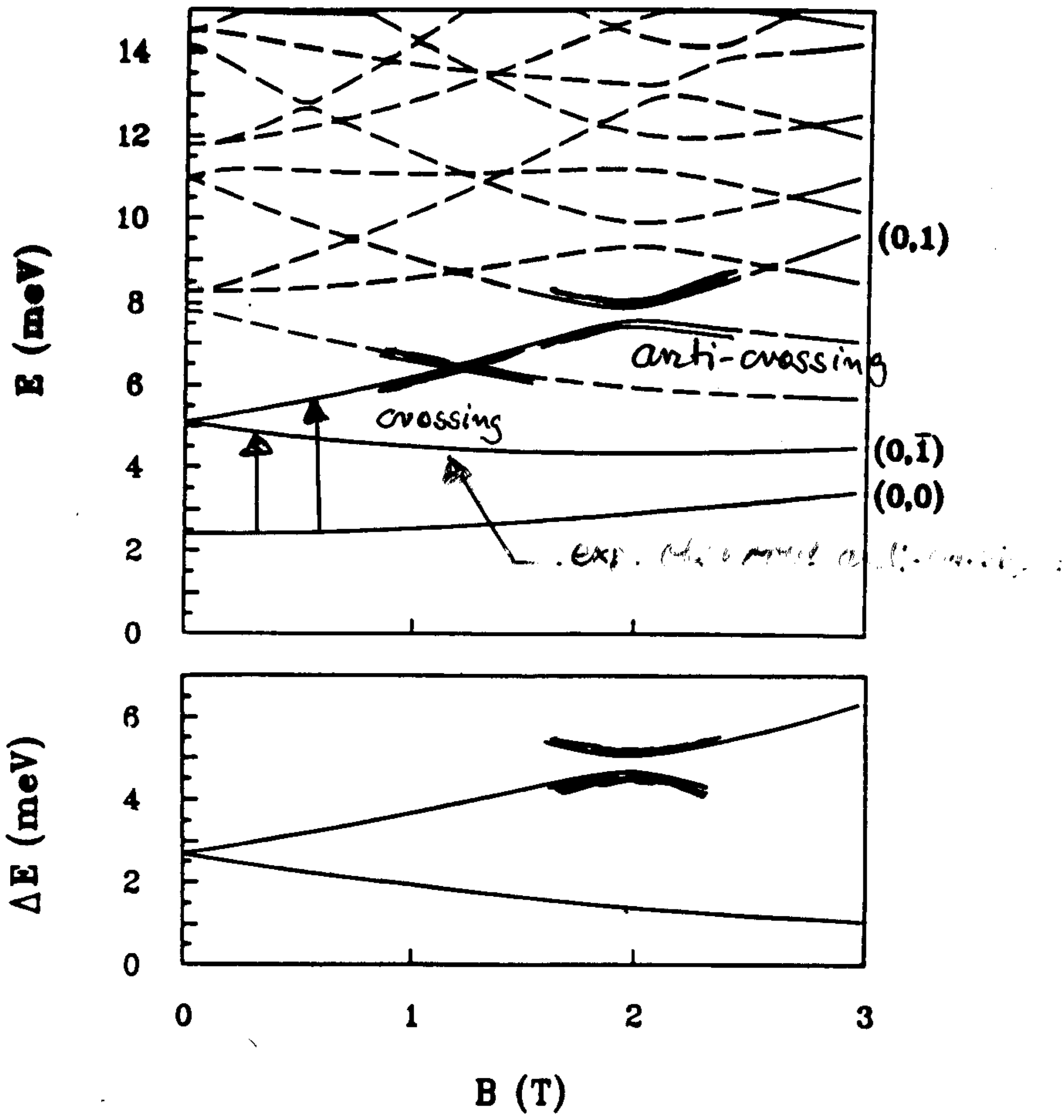
$2\omega_c$ SPLITTING ALSO FOR CIRCULAR SHAPED + NONPARABOLICITY

Deviations from the parabolic potential shape

ONE - ELECTRON





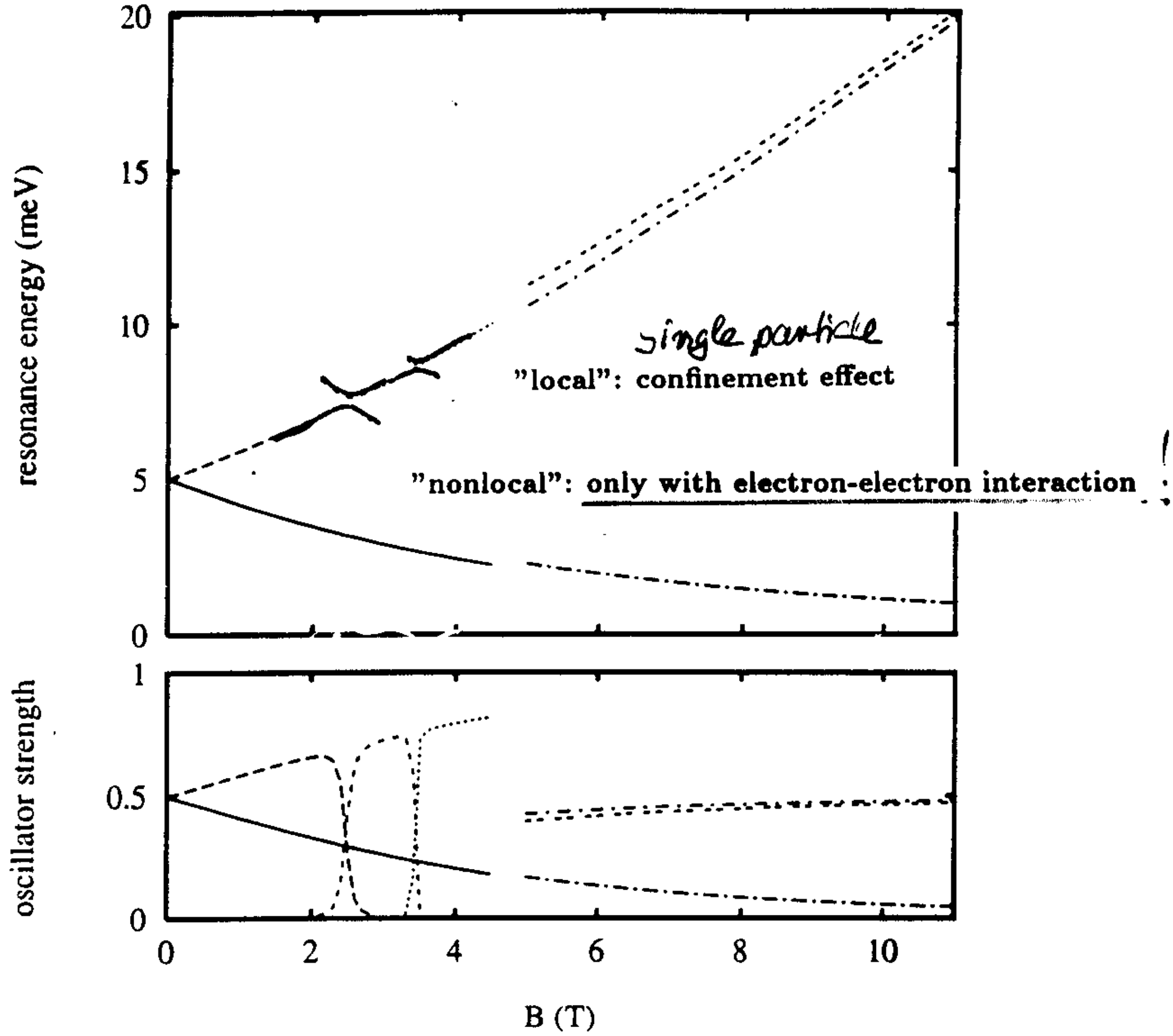


CALCULATED B-DISPERSION IN QUANTUM DOTS WITH SQUARED SYMMETRY

two electrons!

$$V(x,y) = \frac{1}{2} m^* \omega_0^2 (r^2 + a r^4 + b x^2 y^2)$$

D. Pfannkuche and R,R. Gerhardts, PRB 44, 13132 (1991)



DYNAMIC EXCITATIONS IN
IN
SEMICONDUCTOR MICROSTRUCTURES

TWO MODELS:

I.
QUANTUM DOT ATOMS
INCLUDING
ee-INTERACTION

II.
CONFINED PLASMONS

Quantitavely:

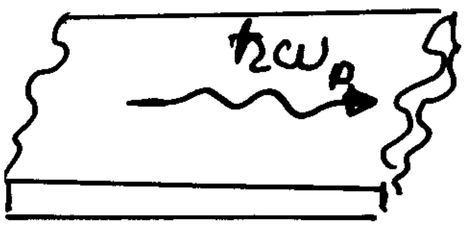
Hartree-Fock and

RPA

COLLECTIVE EXCITATIONS

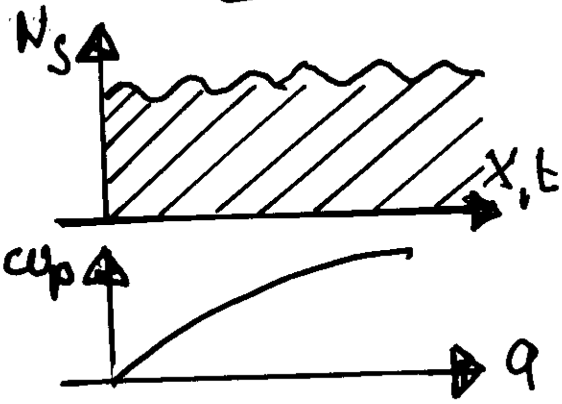
2D-plasmons

2DES:



$$\omega_p^2 = \frac{N_s e^2}{2\varepsilon^* \varepsilon_0 m^*} \cdot q$$

$$e^{-i(qx-\omega t)}$$

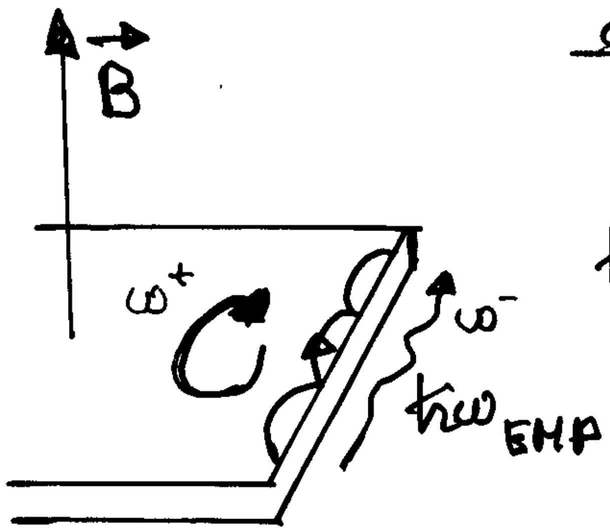


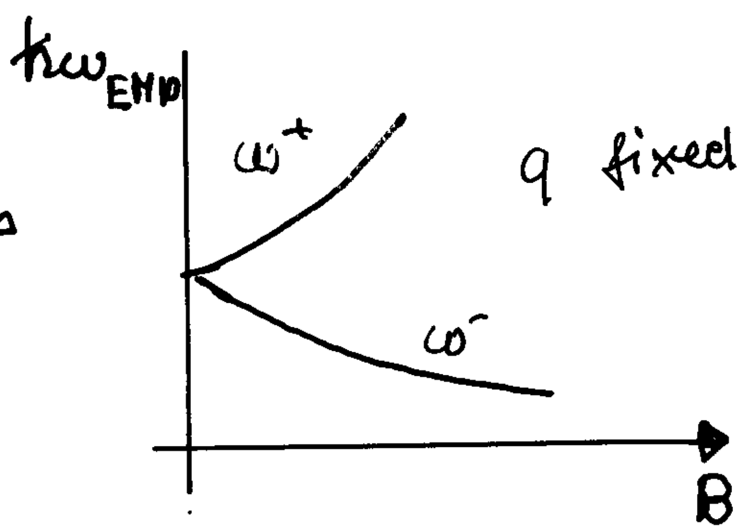
Edge plasmons C ("1½ D")

$$\omega_{EP}^2 = 0{,}81 \frac{N_s e^2}{2\varepsilon^* \varepsilon_0 m^*} \cdot q$$

↑ depends on V_{edge}, q

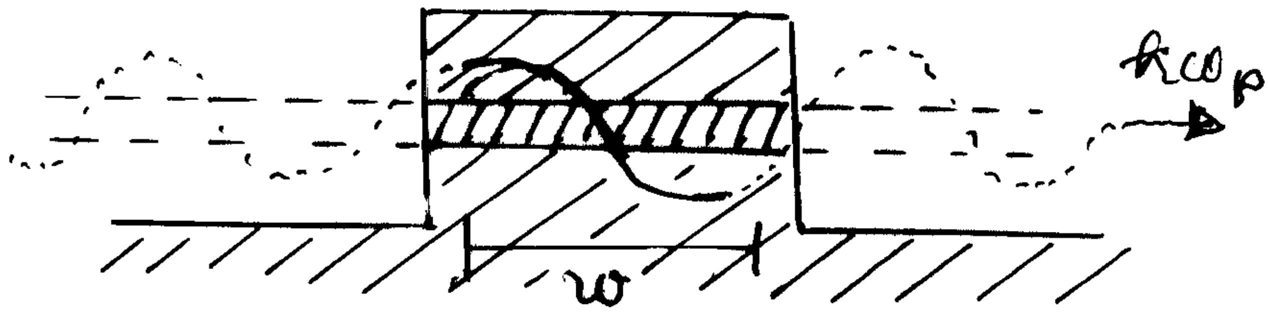
Edge-Magneto-Plasmons





COLLECTIVE EXCITATIONS
IN
QUANTUM WIRES AND DOTS

= CONFINED PLASMONS



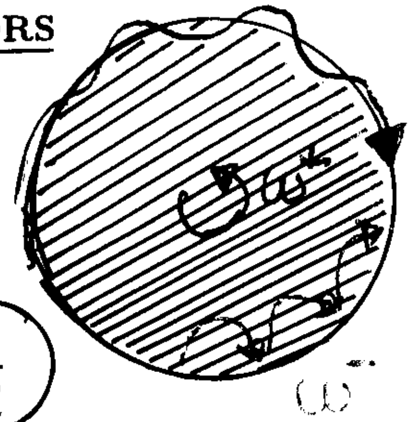
$$\omega_p^2 = \frac{N_s e^2}{2\varepsilon^* \varepsilon_0 m^*} \cdot q$$

$$q = n \cdot \frac{\pi}{w}$$

EDGE MAGNETOPLASMONS IN A 2D DISK:

THE PERIMETER P

QUANTIZES THE ALLOWED q-VECTORS

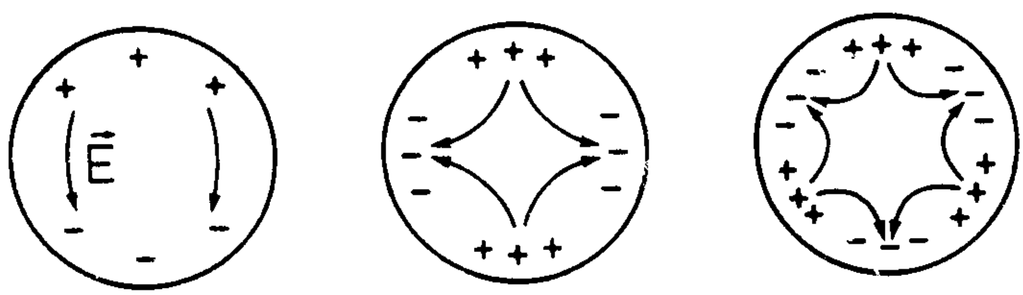


$$n\lambda_n = n2\pi/q_n = 2\pi R = P$$

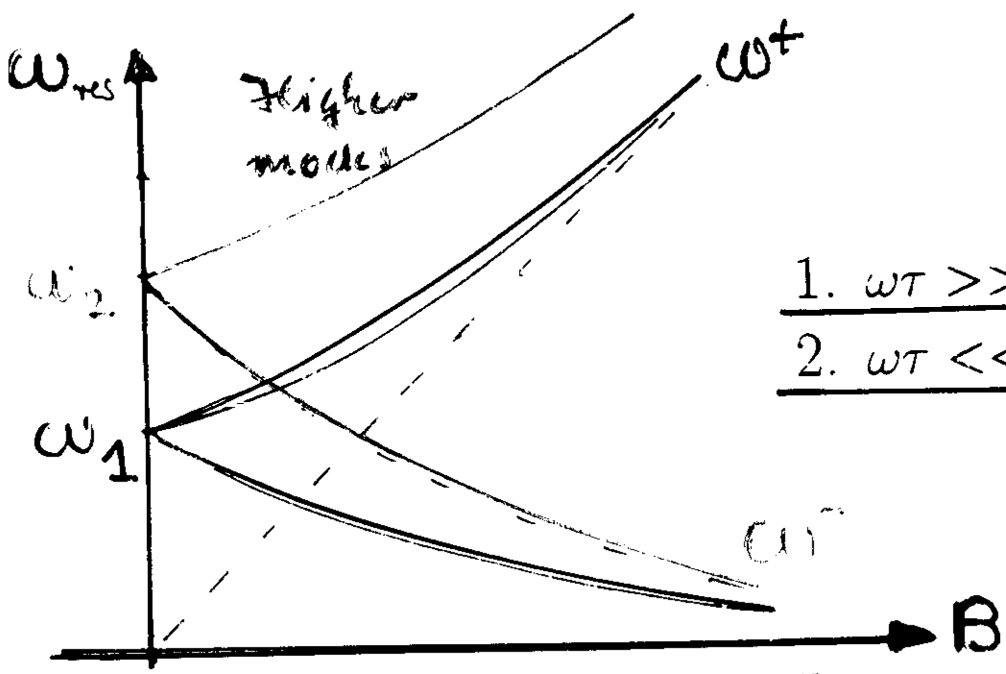
$$q_n = n/R, \quad n = 1, 2, 3, ..$$

$$B = 0: \quad \omega_{pn}^2 = \frac{N_s e^2}{2\epsilon^* \epsilon_0 m^*} * \frac{n}{R}$$

$$B > 0: \quad \omega_{pn}^{(\pm)} = \pm\frac{\omega_c}{2} + \sqrt{\omega_{pn}^2 + (\frac{\omega_c}{2})^2}$$



n=1 n=2 n=3

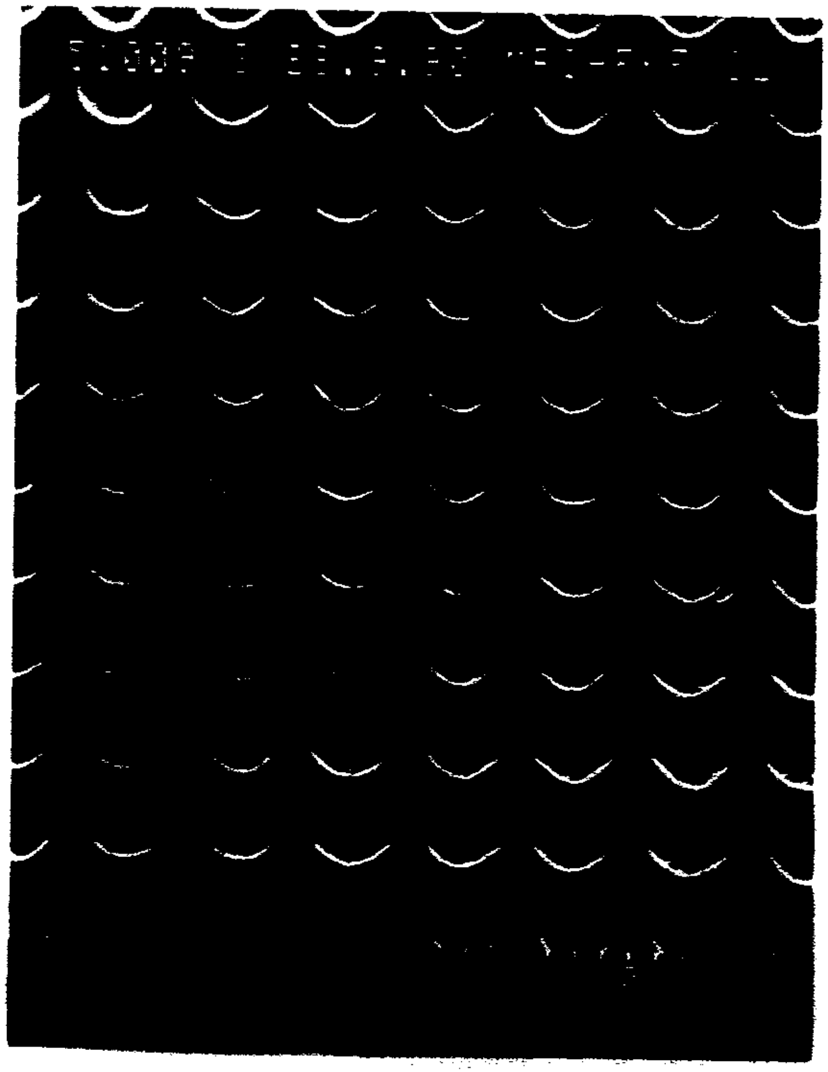


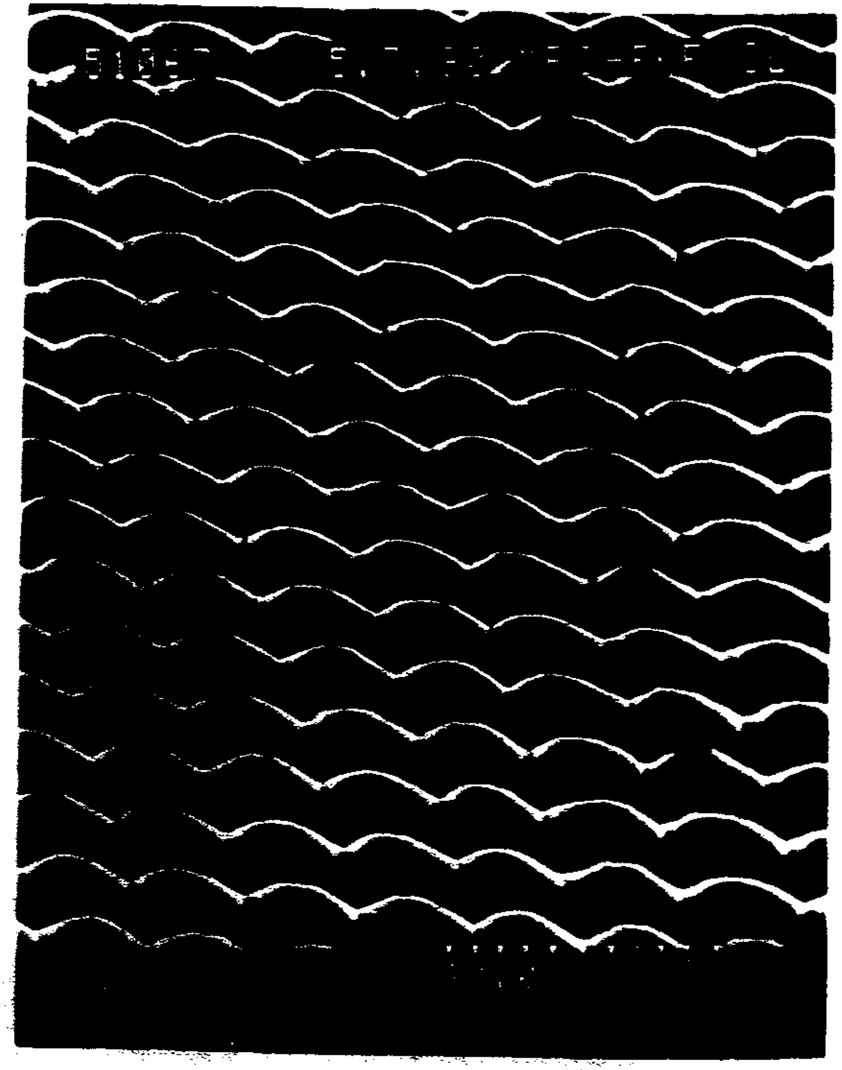
Allen, Störmer, Hwang

1. $\omega\tau >> 1$

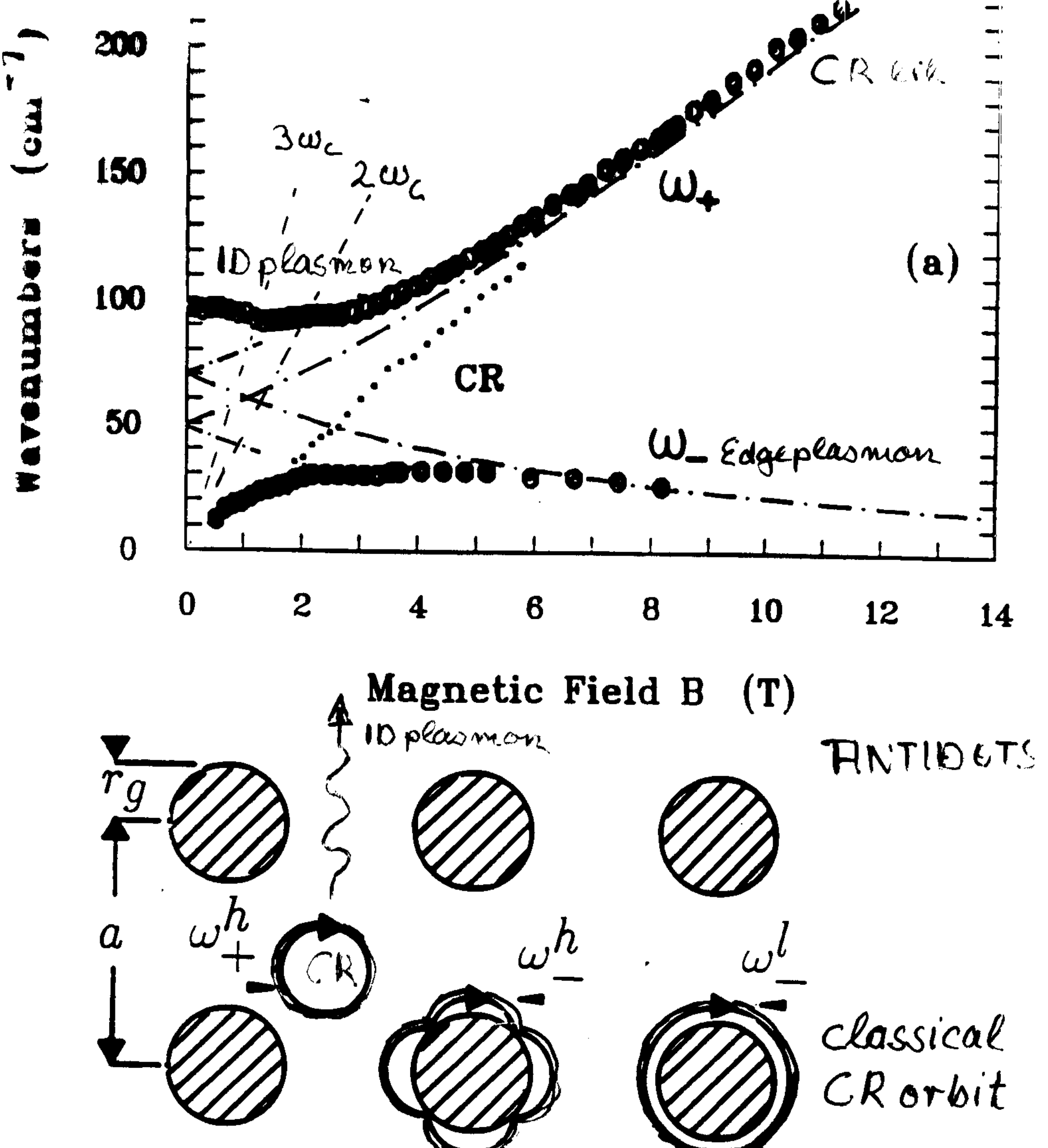
2. $\omega\tau << 1$ QHE

"ANTIDOTS" IN InGaAs-InAlAs-InP





Period $a = 300nm$, hole diameter $2r = 200nm$


Wavenumbers (cm⁻¹)
200
150
100
50
0
0
2
4
6
8
10
12
14
Magnetic Field B (T)
CR
(a)
3ωc
2ωc
1D plasmon
ω+
CR
ω− Edgeplasmon
1D plasmon
ANTIDOTS
rg
a
ω+h
CR
ω−h
ω−l
classical
CR orbit
Dot

DETECTION OF

COMPRESSIBLE
AND
INCOMPRESSIBLE STRIPES

IN QUANTUM DOTS AND ANTIDOTS BY FIR-SPECTROSCOPY

Bollweg et al PRL 96

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'SICAL REVIEW B VOLUME 46, NUMBER 7 15 AUGUST 1992

Electrostatics of edge channels

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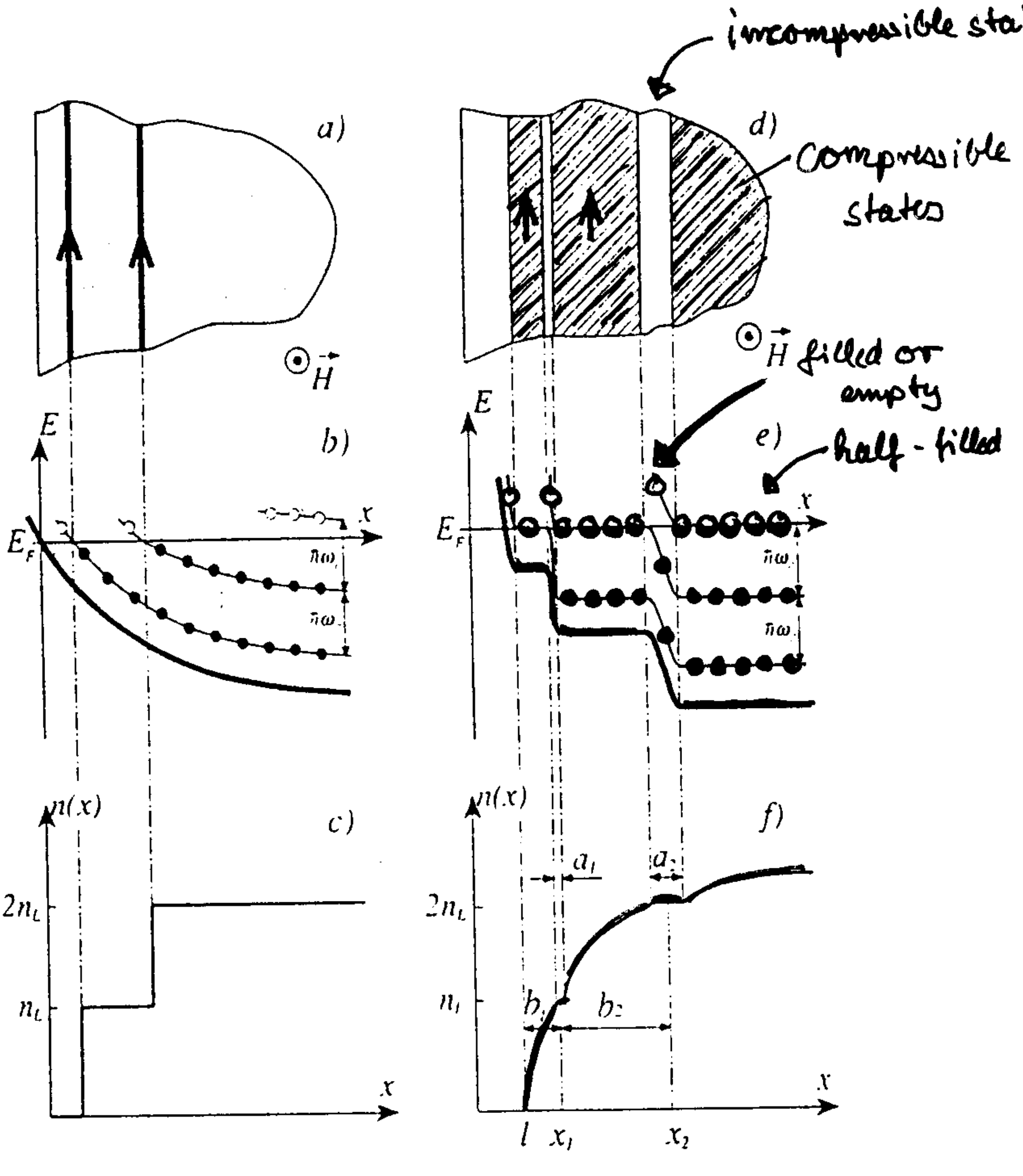


FIG. 1. Structure of spinless edge states in the IQHE regime. (a)–(c) One-electron picture of edge states. (a) Top view on the 2DEG plane near the edge. Arrows designate electron flow direction in the two edge channels. (b) Adiabatic bending of Landau levels along the increasing potential energy near the

Is it possible to see
compressible and incompressible edge states
in quantum dots and antidots
with FIR experiments?

Answer:
In dots or antidots with
parabolic or smooth potential
not

Kohn`s theorem!

To make it observable:
preparation of dots and antidots
with hard wall confinement

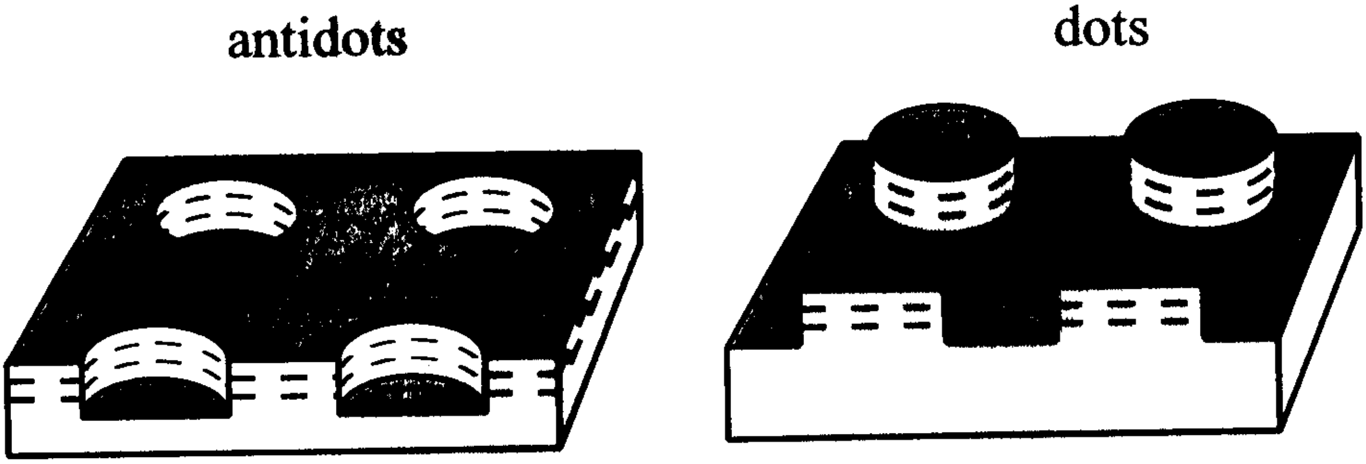
but

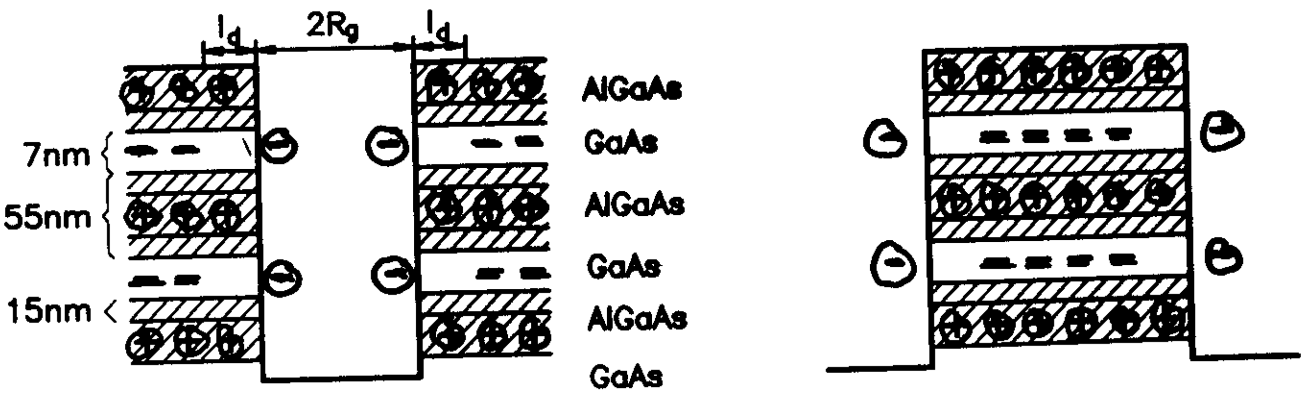
still soft enough

not to 'destroy' the inc/c states!

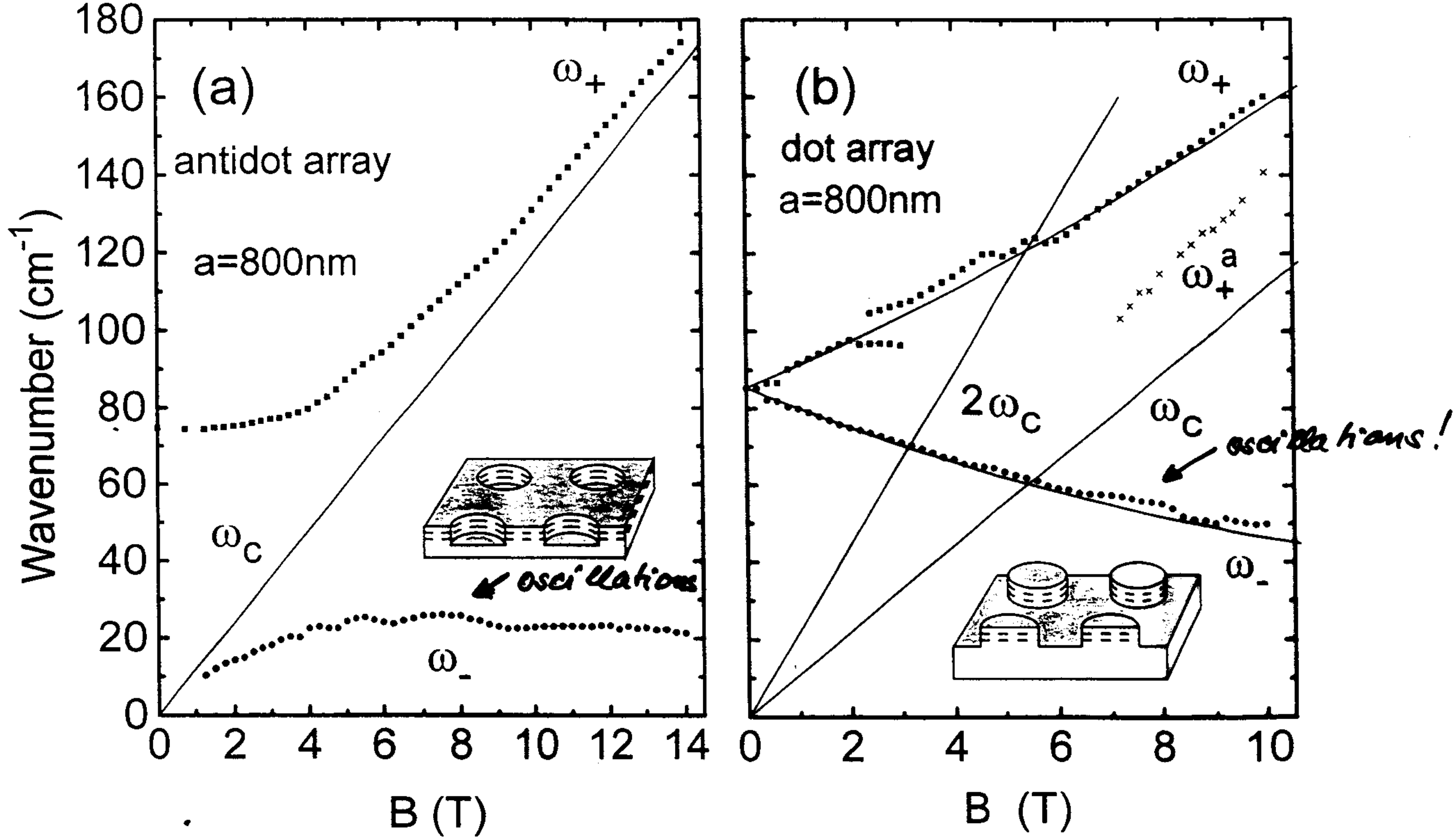
DEEP MESA ETCHED QUANTUM DOTS AND ANTIDOTS WITH THREE DOPING LAYERS

HARD WALL CONFINEMENT





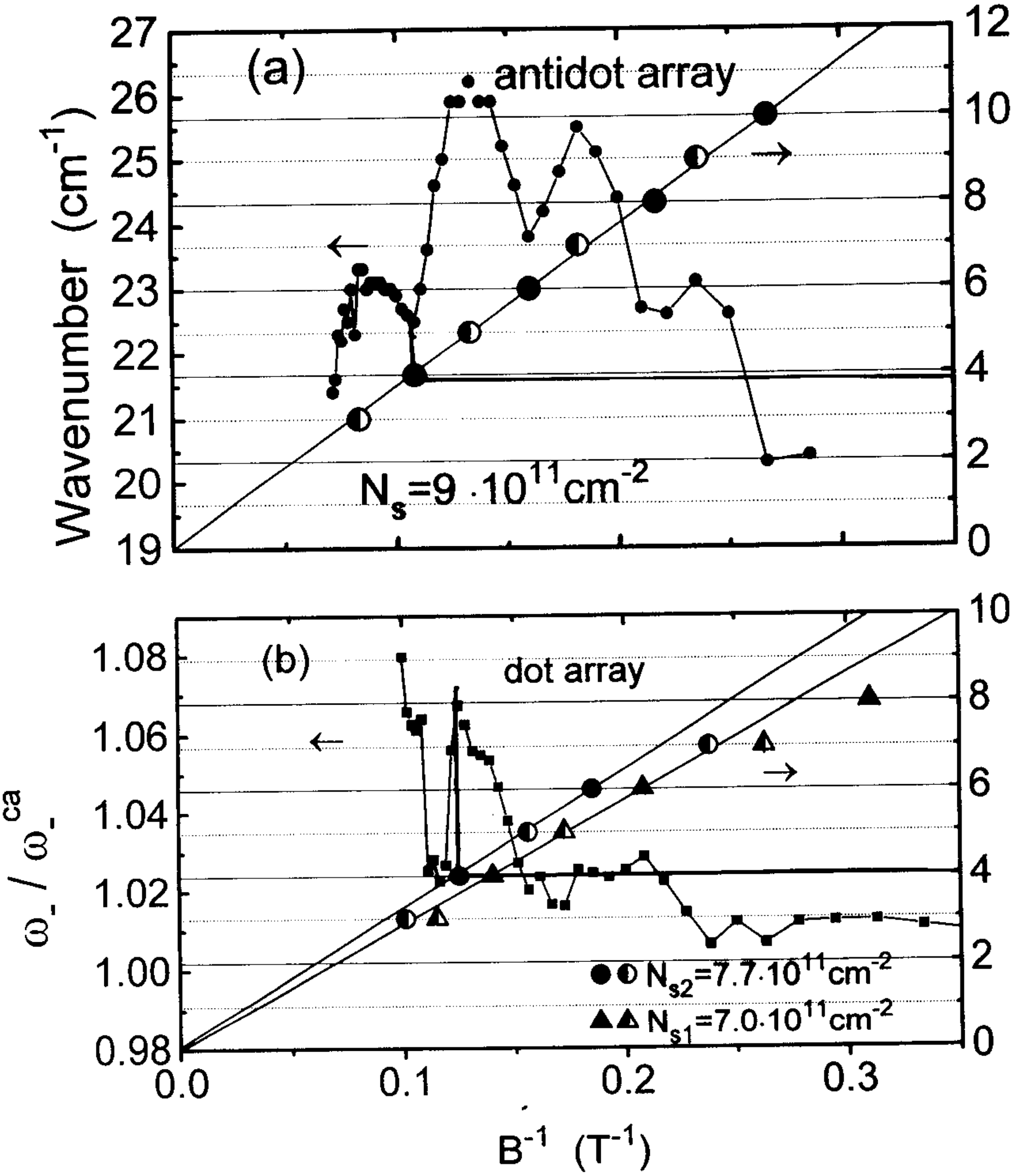
a=800nm, R_g=180nm, $N_S = 9 \cdot 10^{11} cm^{-2}$ **per well**



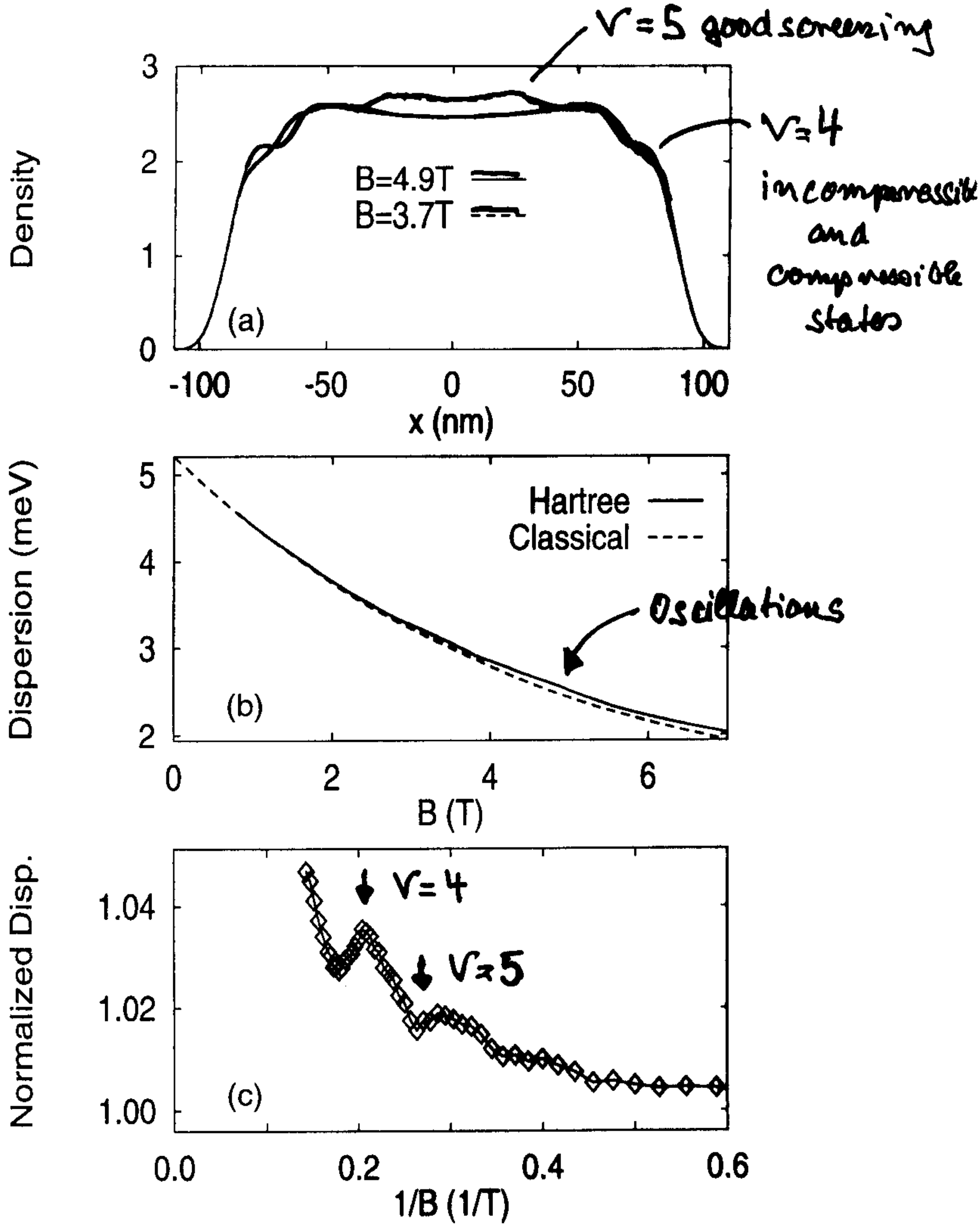
<u>FILLING FACTOR DEPENDENT FREQUENCY</u>
<u>OSCILLATIONS</u>
FOR DOTS AND ANTIDOTS

FAN CHART OF THE FREQUENCY OSCILLATIONS

reverse behaviour for dots and antidots



SELF-CONSISTENT HARTREE CALCULATION
RESONANCE FREQUENCY
NORMALISED RESONANCE FREQUENCY VS 1/B



OPTICAL AND ACOUSTIC PLASMON MODES IN TWO-LAYERED ANTIDOTS SYSTEMS