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SMR.998d - 29

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

"Raman Spectroscopy of Quantum Wires and Dots"

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

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Miniworkshop on Quantum Wells, Dots, Wires and Self-Organizing Nanostructures

21 August 1997

Raman Spectroscopy of Quantum Wires and Dots

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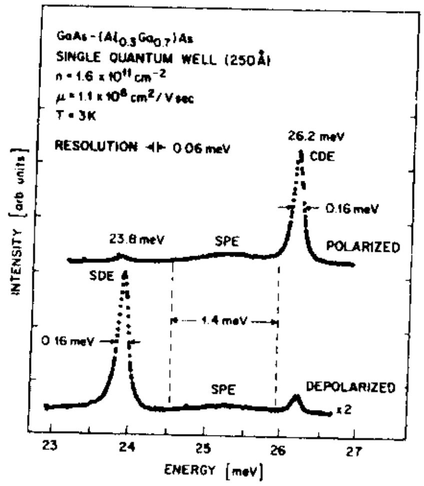
Large Exchange Interactions in the Electron Gas of GaAs Quantum Wells

A. Pinczuk, S. Schmitt-Rink, G. Danan, J. P. Valladares, L. N. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 27 June 1989)

Inelastic-light-scattering measurements show that exchange Coulomb interactions in the two-dimensional electron gas of GaAs microstructures are more important than previously anticipated. Small-wave-vector spectra from modulation-doped quantum wells exhibit unexpected single-particle intersubband transitions in addition to collective spin-density and charge-density modes. From the measured spectral energies the direct and exchange intersubband Coulomb interactions are determined and found to be of comparable strengths.



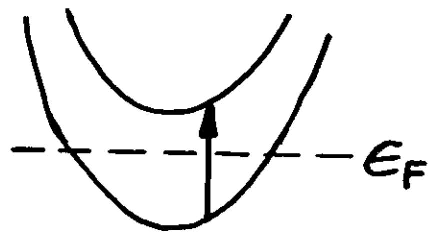


FIG. 1. Inelastic-light-scattering spectra of intersubband excitations of the high-mobility 2D electron gas in a GaAs quantum well. The peaks of spin-density excitations (SDE), charge-density excitations (CDE), and single-particle excitations (SPE) are shown.

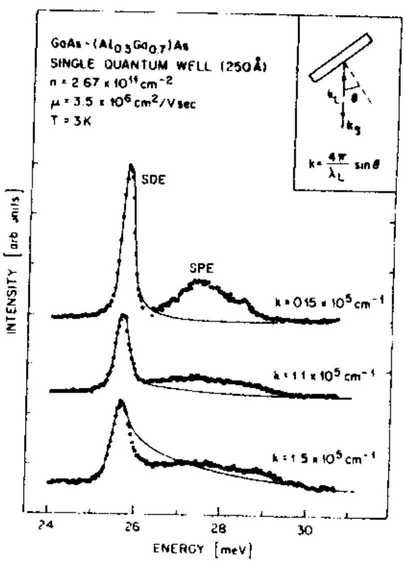


FIG. 2. Depolarized light-scattering spectra of intersubband excitations for several values of the scattering wave vector k. The lines are fits of SDE spectra using Eqs. (1)-(4). Inset: The scattering geometry and the expression for k.

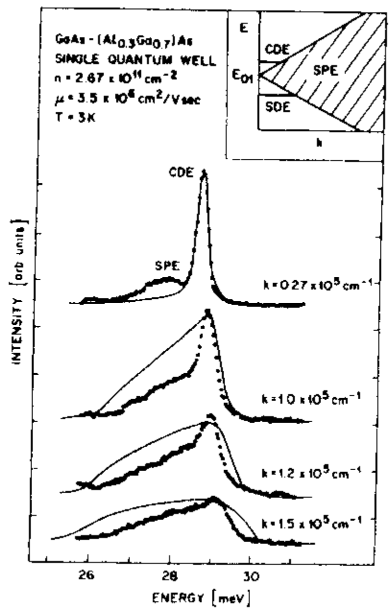


FIG. 3. Polarized light-scattering spectra of intersubband excitations for several values of the scattering wave vector k. The lines are fits of CDE spectra using Eqs. (1)-(4). Inset: A sketch of the k dependence of intersubband excitations in the long-wavelength limit $k \ll k_F$.

Single-Particle Excitations in Quasi-Zero- and Quasi-One-Dimensional Electron Systems

R. Strenz, U. Bockelmann, F. Hirler, G. Abstreiter, G. Böhm, and G. Weimann

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(Received 19 July 1994)

Resonant inelastic light scattering is used to probe electronic excitations in shallow etched GaAs/AlGaAs quantum dots and wires. In both types of structures, intersubband excitations are observed in depolarized scattering geometries. They show significant blueshift with decreasing confinement length. In dot structures these transitions appear as dispersionless, whereas in wires they show strong broadening and an intensity dip at the energetic center of the excitation with increasing wave vector parallel to the wires, as expected for single-particle excitations. Their line shape correlates with the linear wave vector dispersion of additionally observed intrasubband excitations.

PACS numbers: 71.50.+t, 78.30.Fs

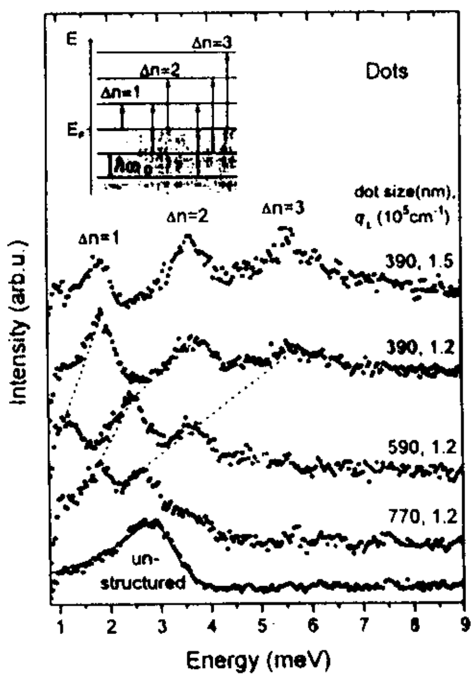

FIG. 1. Depolarized light scattering by interlevel excitations in quantum dots. The two parameters at each spectrum denote the geometrical dot size and wave vector. The lowest spectrum shows the reference measurement of the as-grown sample and a line shape fit (continuous line). All contributing transitions are schematically shown in the inset.

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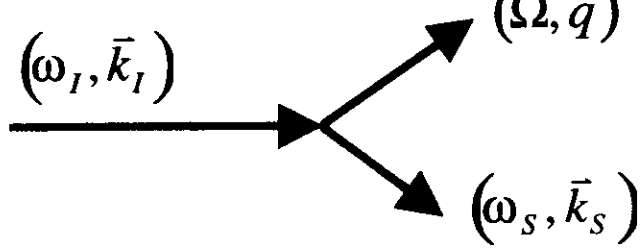
Raman Spectroscopy of Quantum Wires and Dots

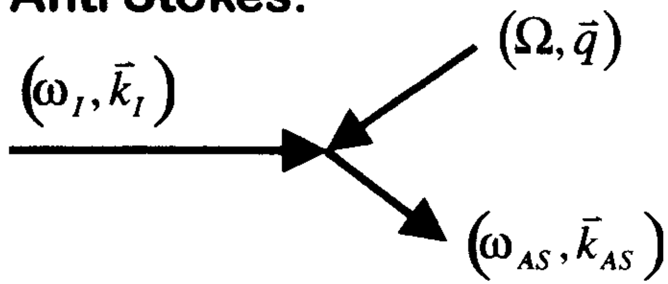
- **Motivation**
- **Introduction to Raman spectroscopy of semiconductor nanostructures**
- **Experimental setup and sample preparation**
- **Quasi-atomic finestructure in quantum dots**
- **One-dimensional plasmons in magnetic fields**
- **Summary**

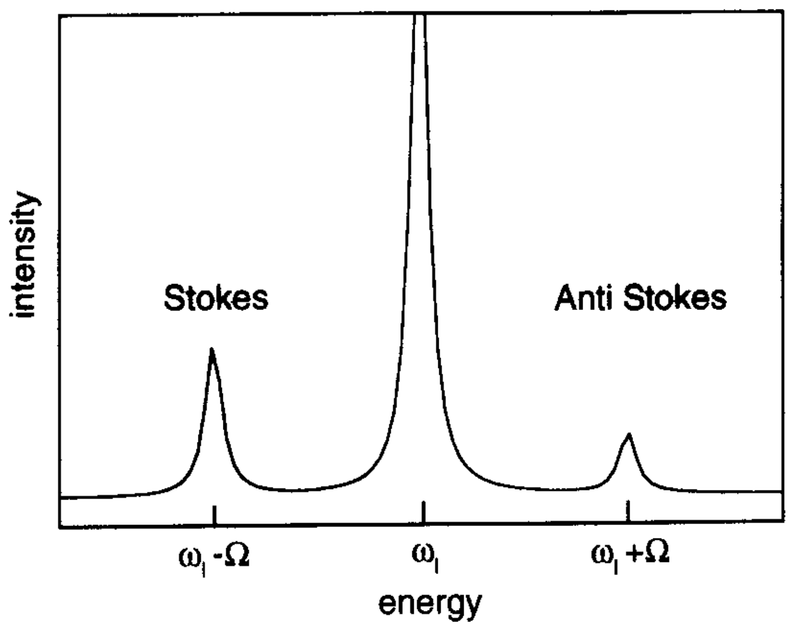
Raman scattering

Stokes:



Anti Stokes:





Energy conservation:

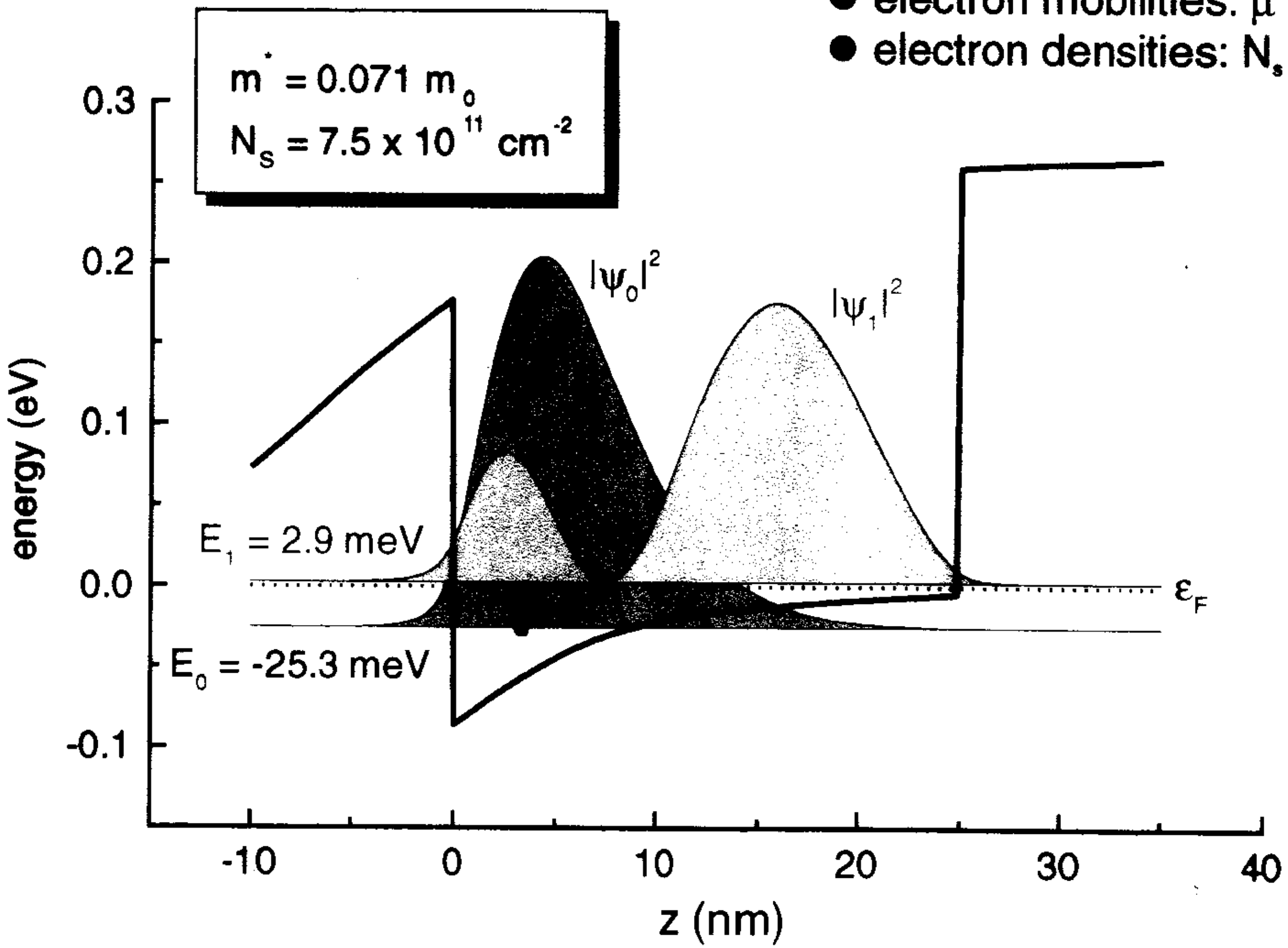
$$\hbar\omega_S = \hbar\omega_I \mp \hbar\Omega$$

Momentum conservation:

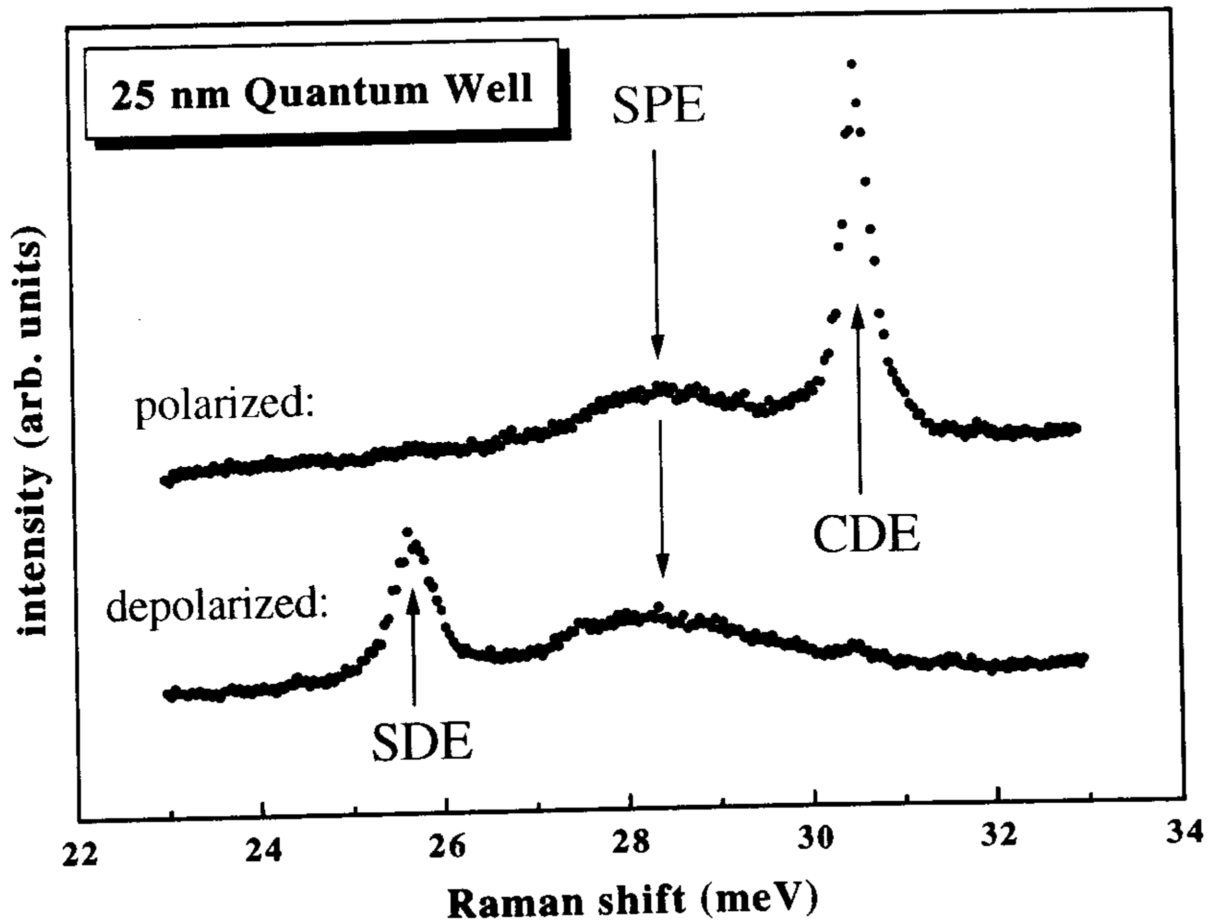
$$\vec{k}_S = \vec{k}_I \mp \vec{q} \quad \left(+\vec{G}\right)$$

Quantum well samples for Raman experiments

- one-sided modulation-doped SQWs
- 25 nm GaAs wells
- electron mobilities: $\mu = 7 \times 10^5$ cm^2 V^{-1} s^{-1}
- electron densities: $N_s = 4 - 7.5 \times 10^{11}$ cm^{-2}



Resonant Raman scattering on quantum wells



Energies of collective intersubband excitations in a quantum well

$$\omega_{CDE}^2 = \omega_{01}^2 + N_s \omega_{01} \left(\frac{\alpha_{01}}{\varepsilon(\omega)} - \beta_{01} \right)$$

$$\omega_{SDE}^2 = \omega_{01}^2 - N_s \omega_{01} \beta_{01}$$

Resonant inelastic light scattering

Coupling of radiation with electron system:

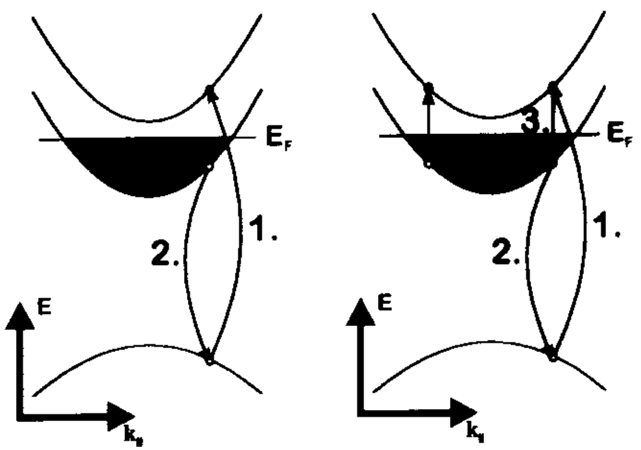
$$H = \frac{1}{2m}\sum_i \left[\left(\vec{p}_i + e\vec{A} \right)^2 + U(\vec{r}_i) \right] + H_{e-e} + H_{e-ph}$$

$$\frac{\vec{A}^2}{2m} + \frac{\vec{p}\vec{A}}{m}$$

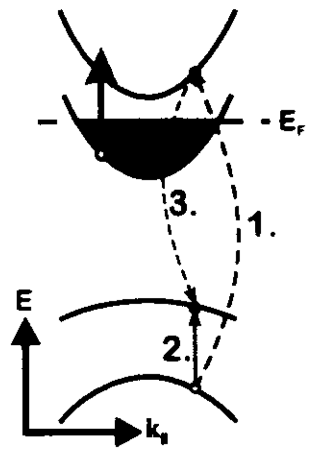
$$\frac{\vec{A}^2}{2m} + \frac{\vec{p}\vec{A}}{m} + H_{e-e}$$

$$\gamma_{if} \propto \sum_m \frac{\langle i|\vec{p}\vec{A}|m\rangle\langle m|\vec{p}\vec{A}|f\rangle}{E_m - E_f - \hbar\omega_I}$$

$$\gamma_{if} \propto \sum_{m,n} \frac{\langle i|\vec{p}\vec{A}|m\rangle\langle m|H_{e-e}|n\rangle\langle n|\vec{p}\vec{A}|f\rangle}{(E_n - E_f - \hbar\omega_I)(E_i - E_m - \hbar\omega_S)} + \ldots$$



CDE, SDE, SPE (extreme resonance)



CDE, SDE

Electronic Raman scattering

Scattering cross section:

$$\frac{\partial^2\sigma}{\partial\omega\partial\Omega} \propto \mathrm{Im}\{\Pi(q,\omega)\}$$

$\Pi(q,\omega)$: polarization function

Charge-density fluctuations: ($\omega_i << E_{Gap}$)

$$\frac{\partial^2\sigma}{\partial\omega\partial\Omega} \propto (\vec{e}_i \cdot \vec{e}_s)^2\, \mathrm{Im}\{\Pi_{CDE}(q,\omega)\} = (\vec{e}_i \cdot \vec{e}_s)^2\, \mathrm{Im}\left\{\frac{\Pi_0}{1+\gamma_{CDE}\Pi_0}\right\}$$

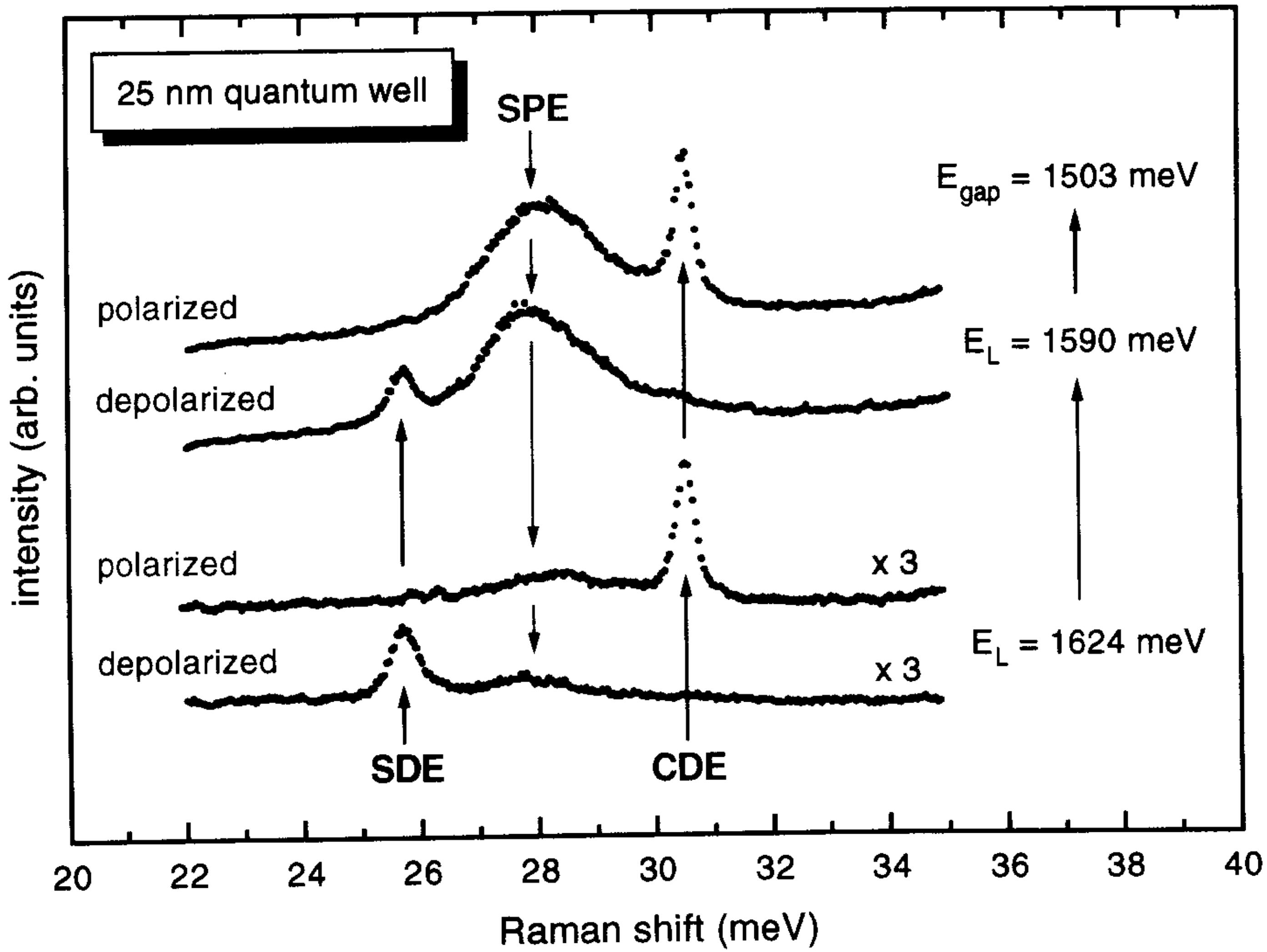
$$\vec{e}_i \| \vec{e}_s$$

Spin-density fluctuations: ($\omega_i << E_{Gap}$)

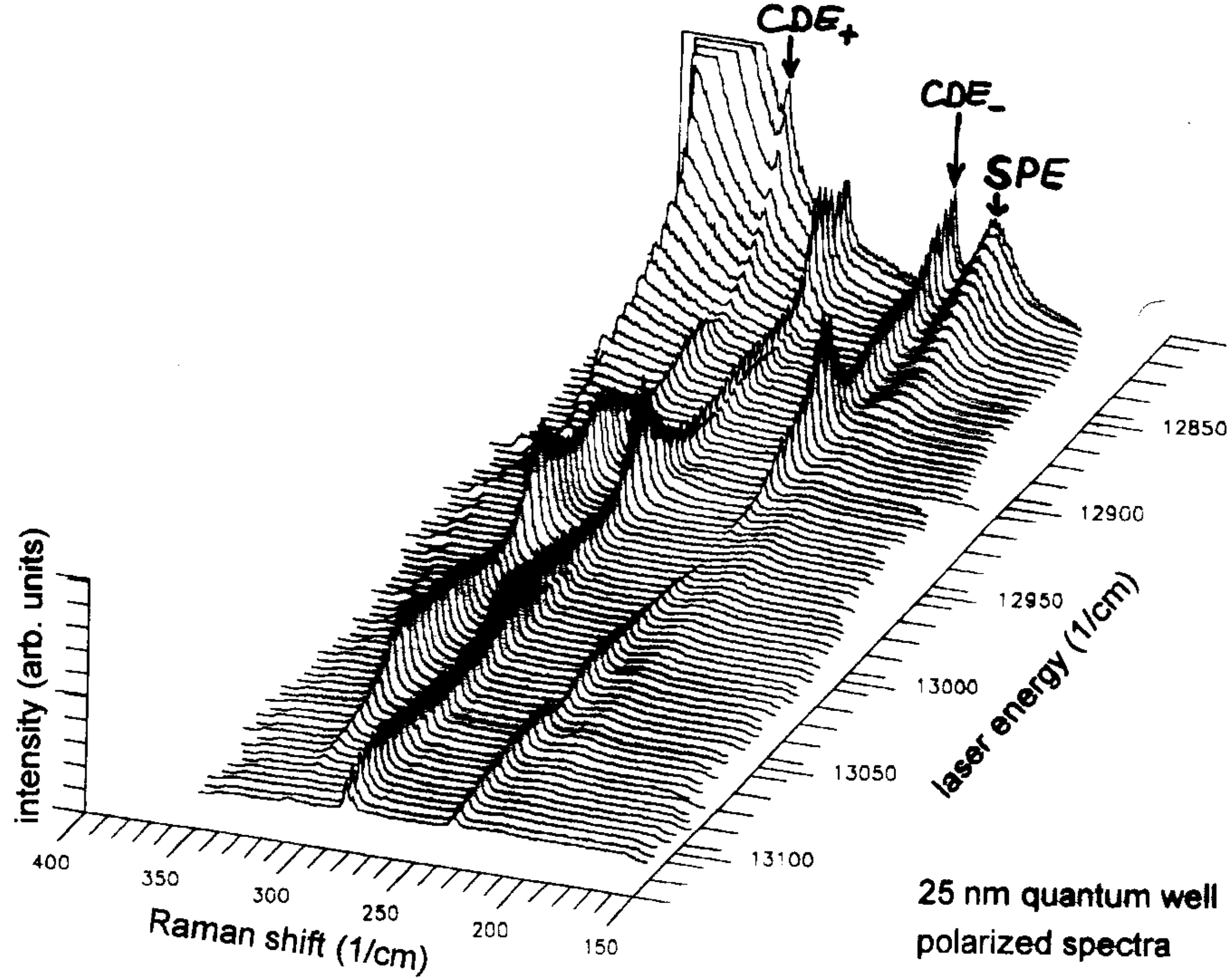
$$\frac{\partial^2\sigma}{\partial\omega\partial\Omega} \propto (\vec{e}_i \times \vec{e}_s)^2\, \mathrm{Im}\{\Pi_{SDE}(q,\omega)\} = (\vec{e}_i \times \vec{e}_s)^2\, \mathrm{Im}\left\{\frac{\Pi_0}{1+\gamma_{SDE}\Pi_0}\right\}$$

$$\vec{e}_i \perp \vec{e}_s$$

Close-to-resonant excitation enhances single-particle effects

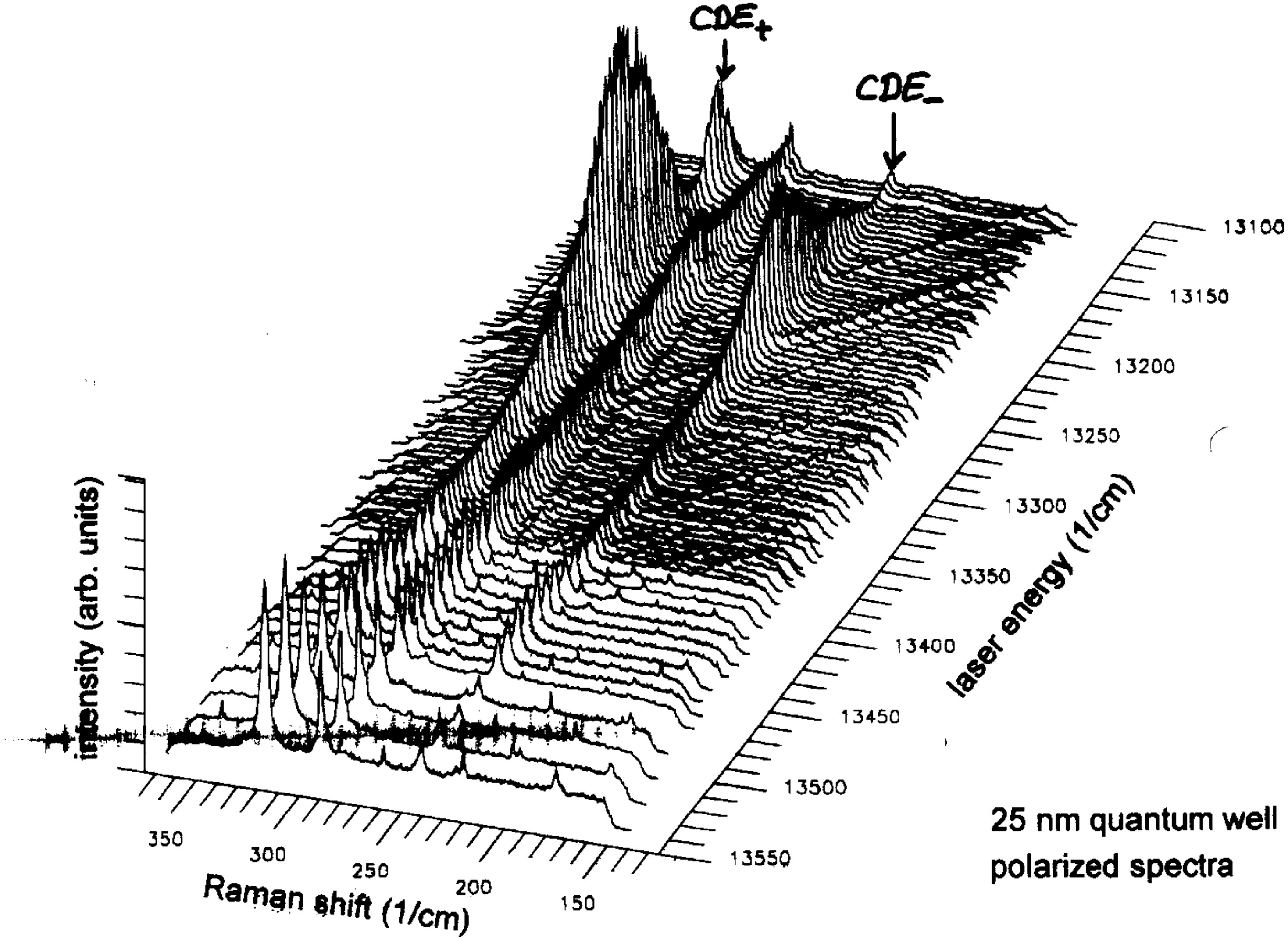


Resonant Raman scattering on quantum well



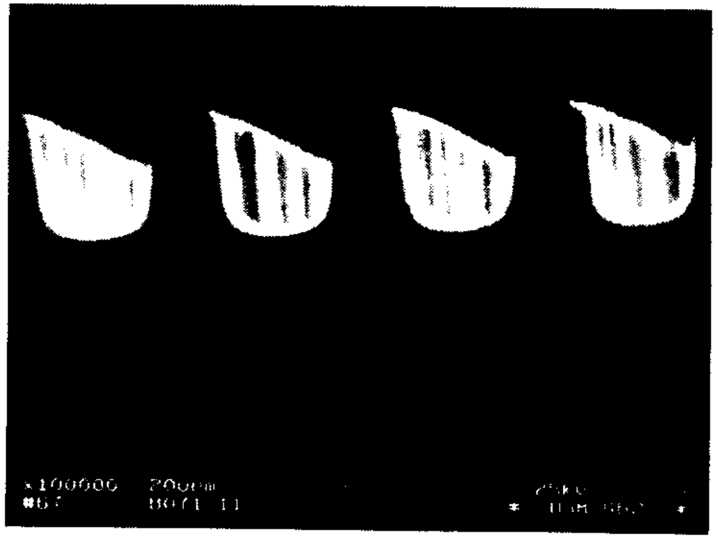
25 nm quantum well
polarized spectra

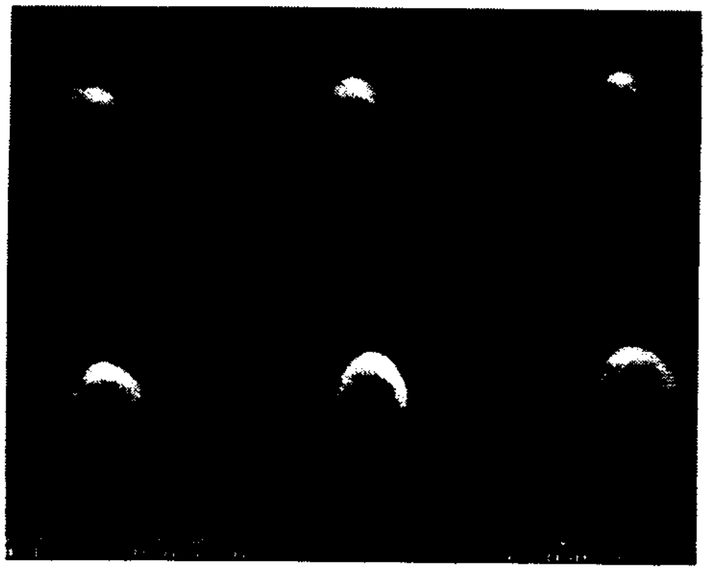
Resonant Raman scattering on quantum well

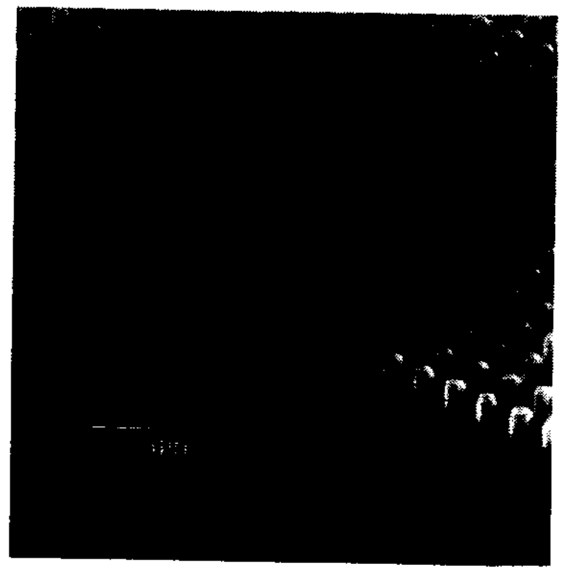


25 nm quantum well
polarized spectra

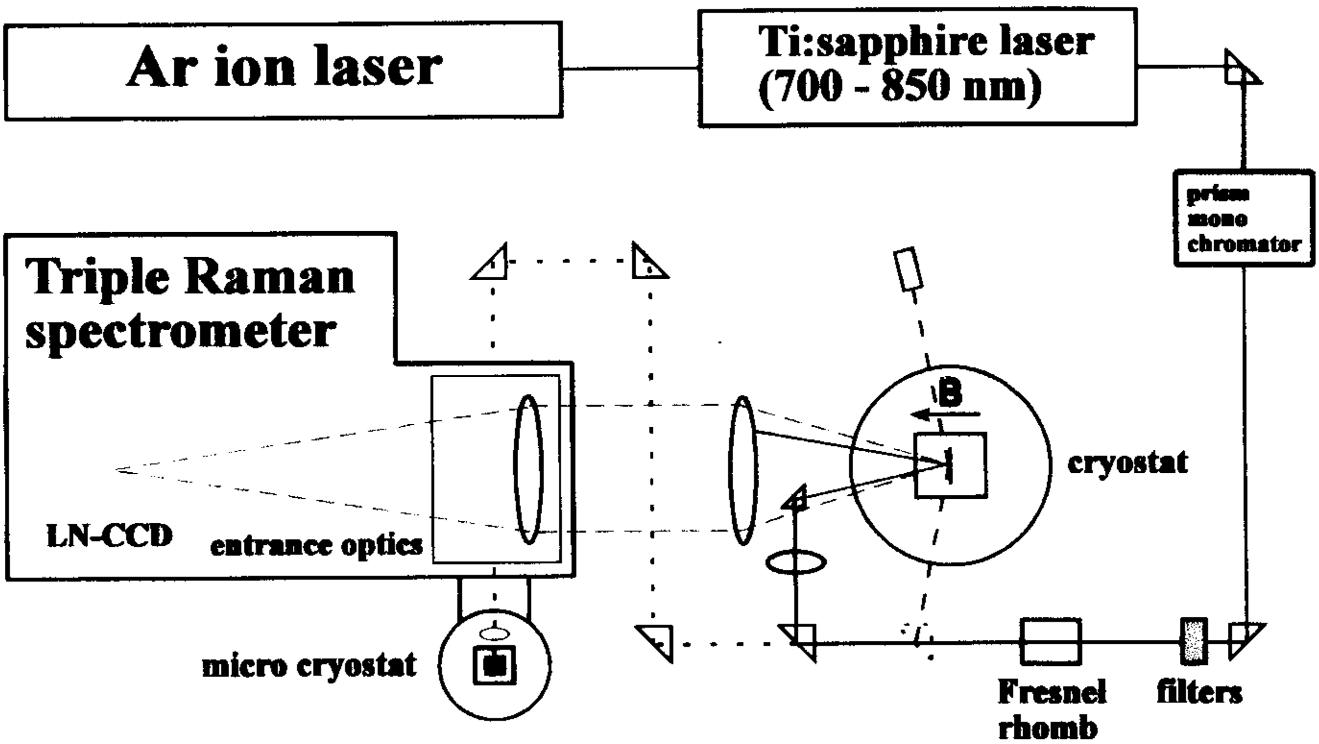
SEM pictures of deep-etched structures





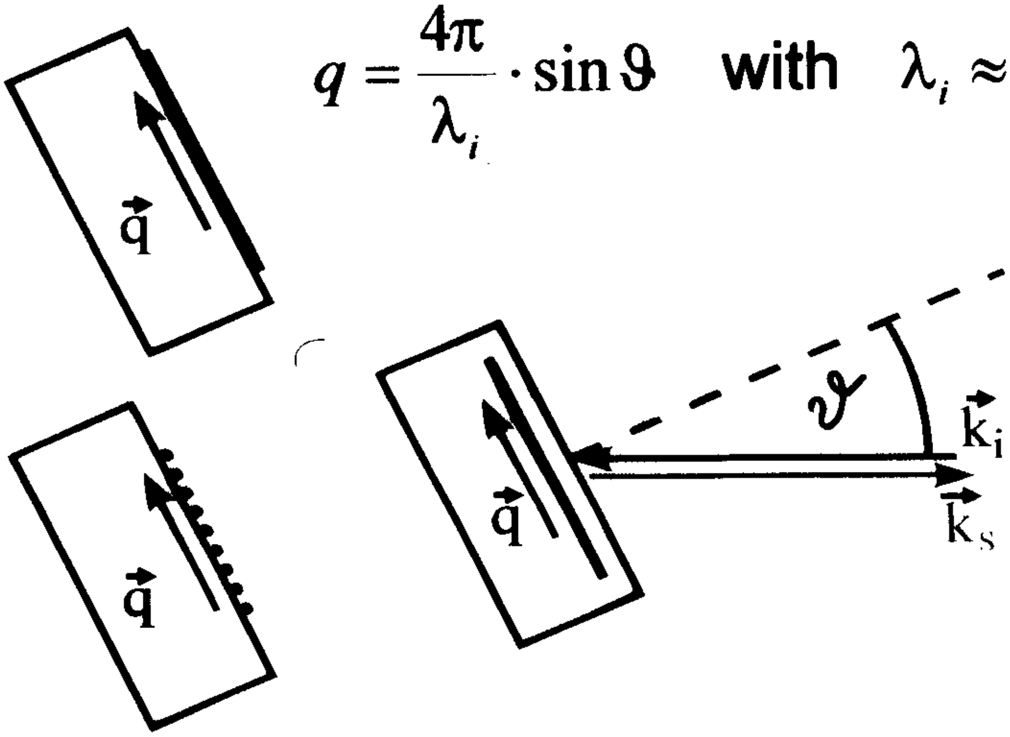


Experimental setup

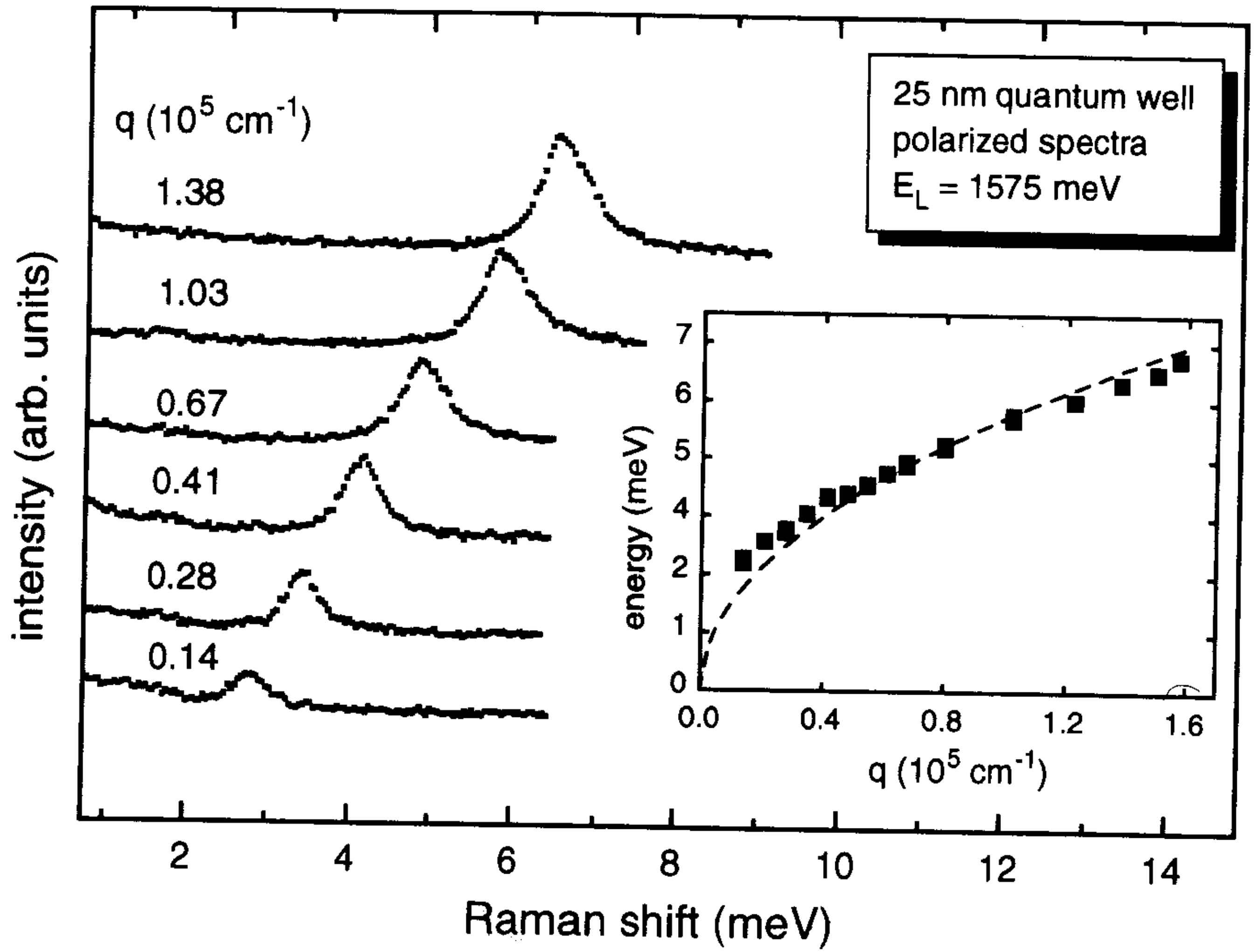


Scattering geometry:

$$q = \frac{4\pi}{\lambda_i} \cdot \sin\vartheta \quad \text{with} \quad \lambda_i \approx \lambda_s$$

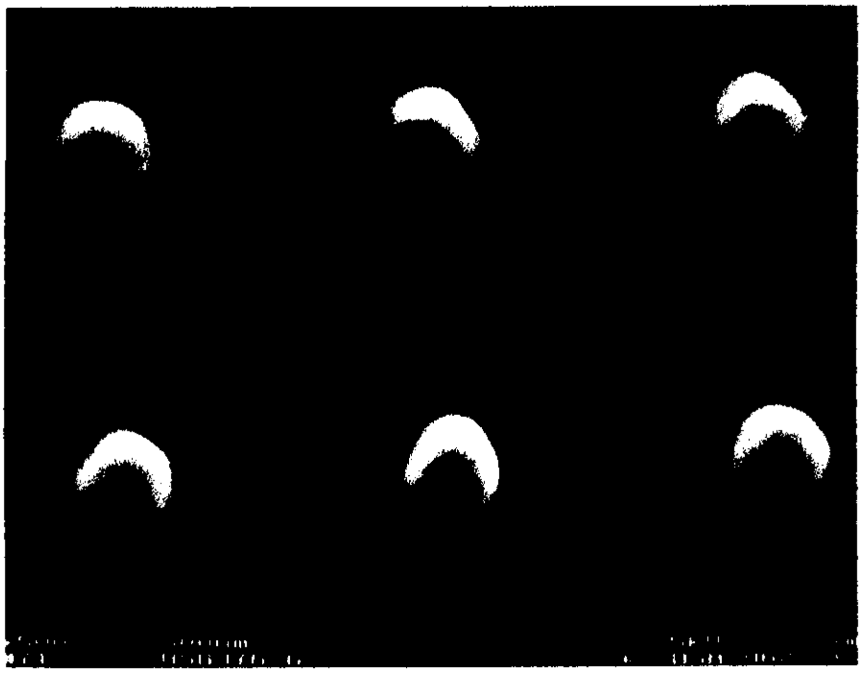


2D intraband plasmon in a single quantum well



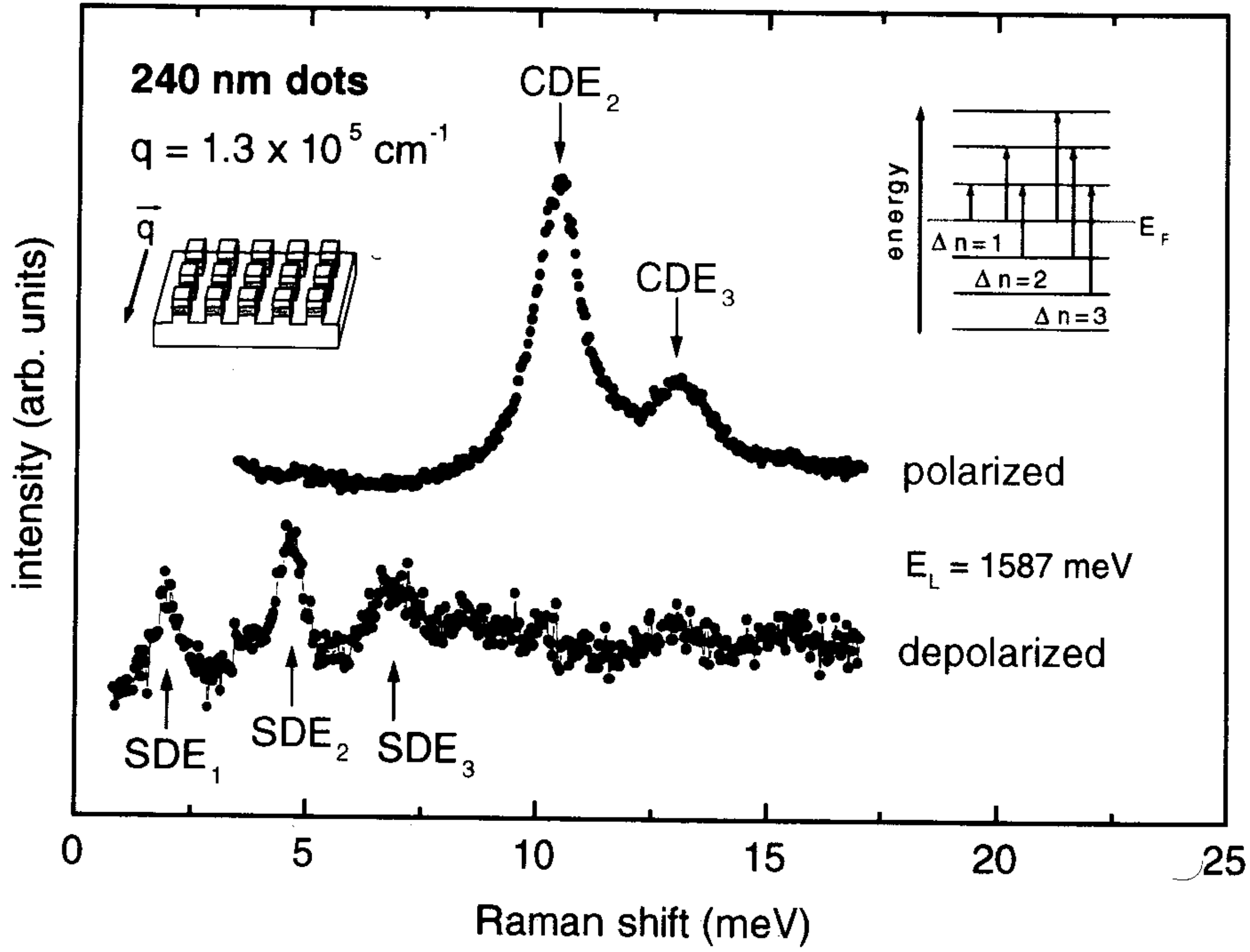
SEM pictures of quantum dots:

8376-6: (240 nm dots)

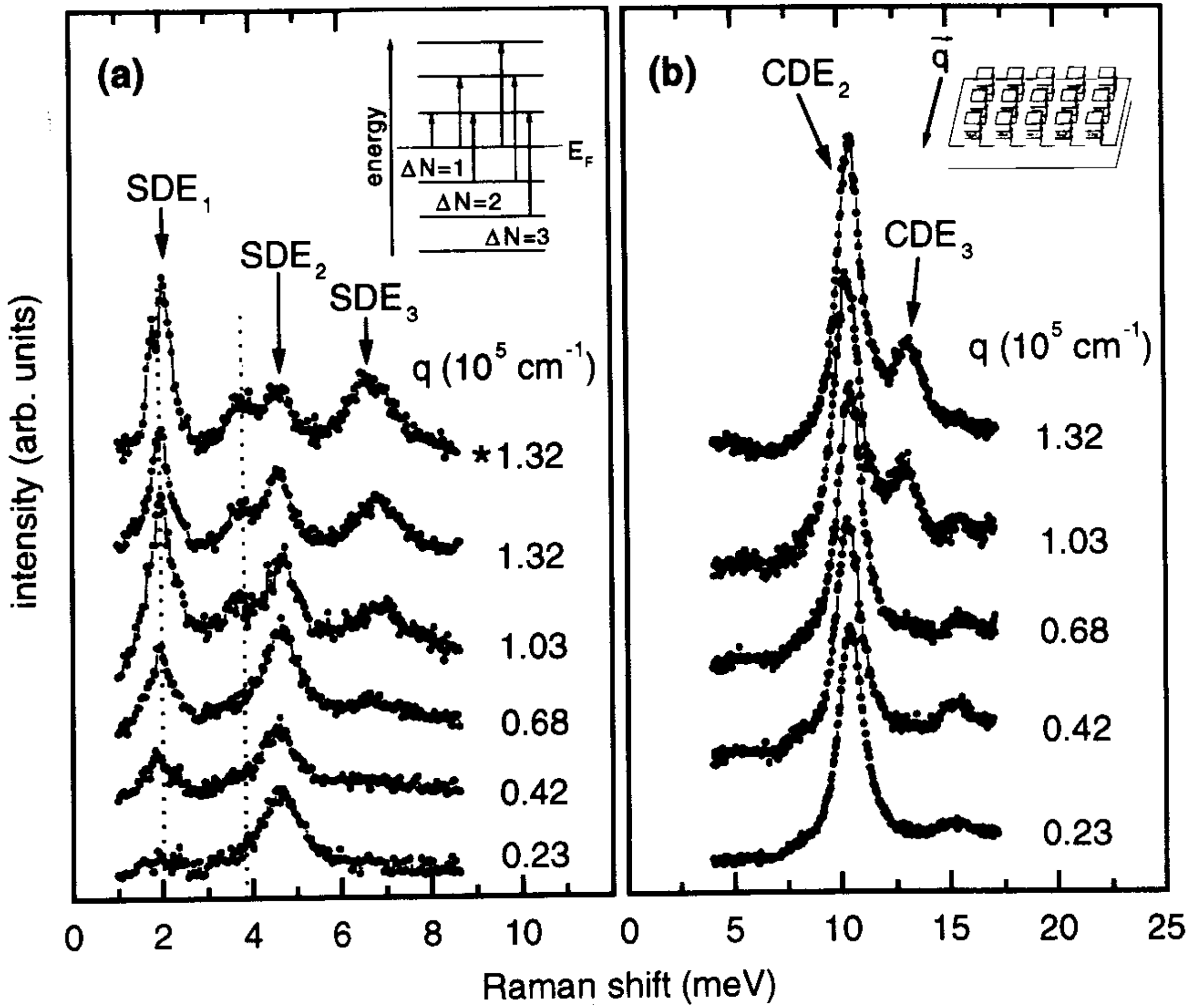


8376-7: (400 nm dots)

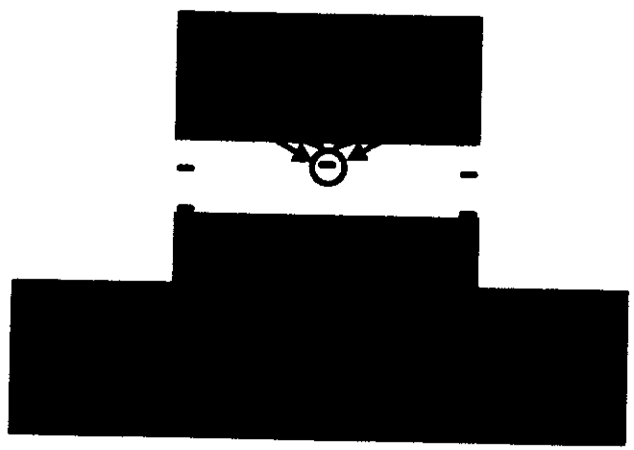
Raman scattering on quantum dots



Quasi-atomic finestructure in quantum dots



External lateral potential in a quantum dot



External lateral potential:

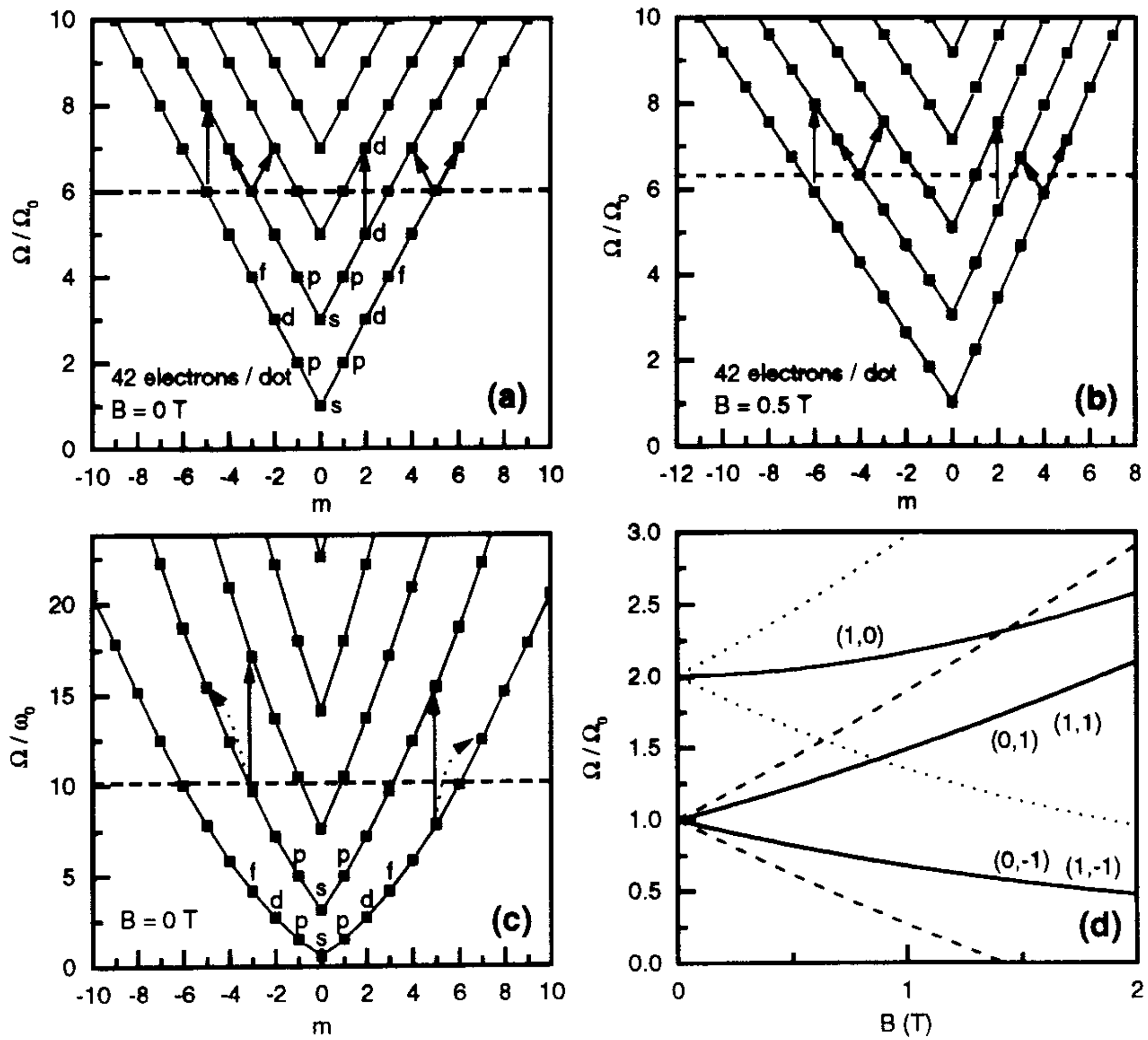
$$V(r) = \tfrac{1}{2} m^{*} \Omega_0^2 \; r^2$$

Energy eigenvalues:

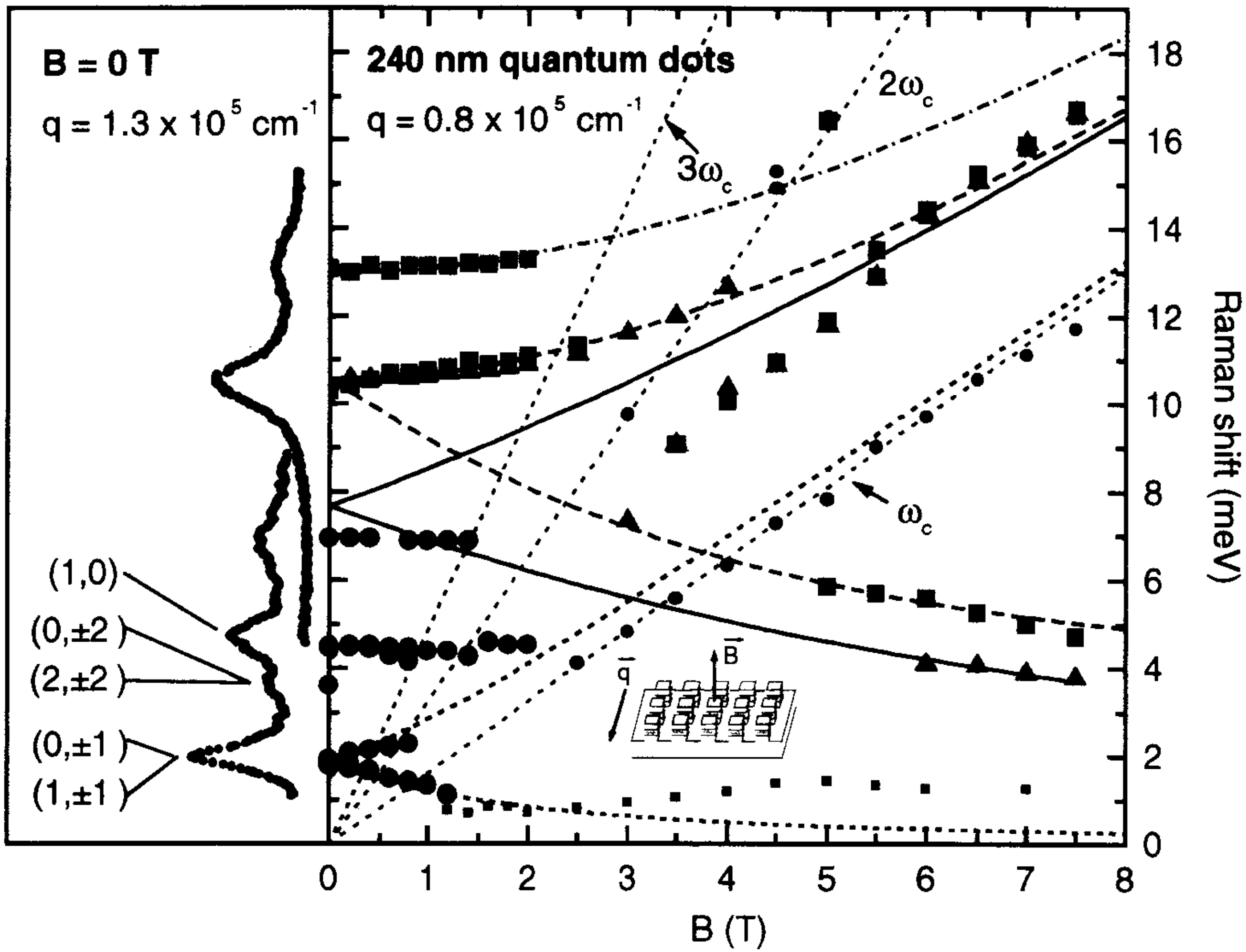
$$E_{nm} = (2n + |m| + 1)\hbar\Omega_0$$

n: radial quantum number
m: azimuthal quantum number

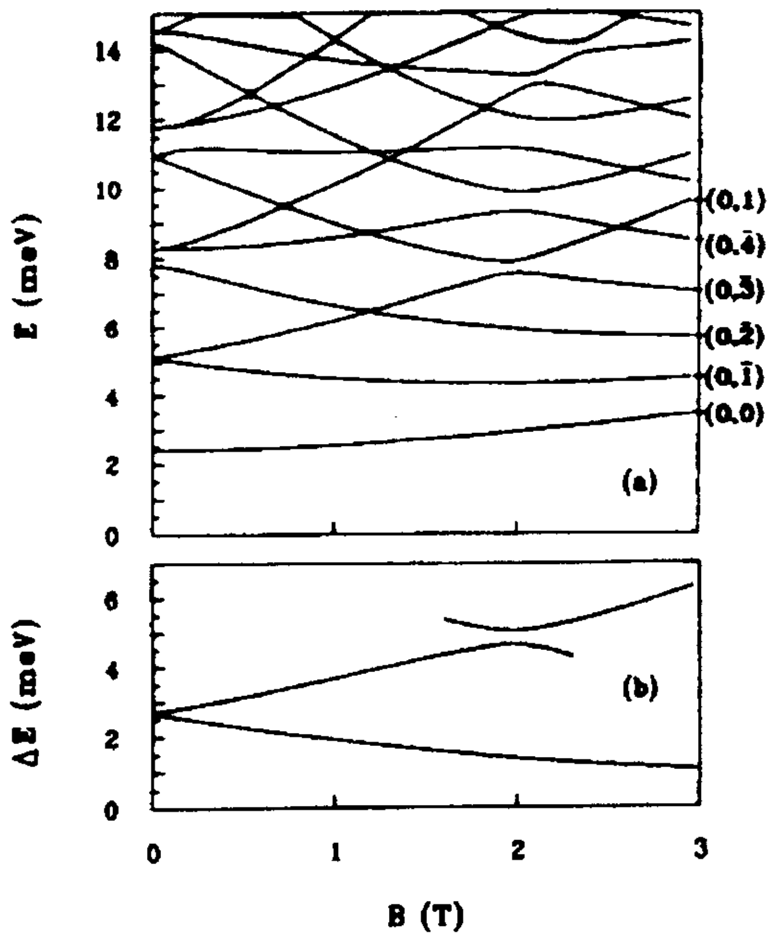
Quasi-atomic finestructure in quantum dots



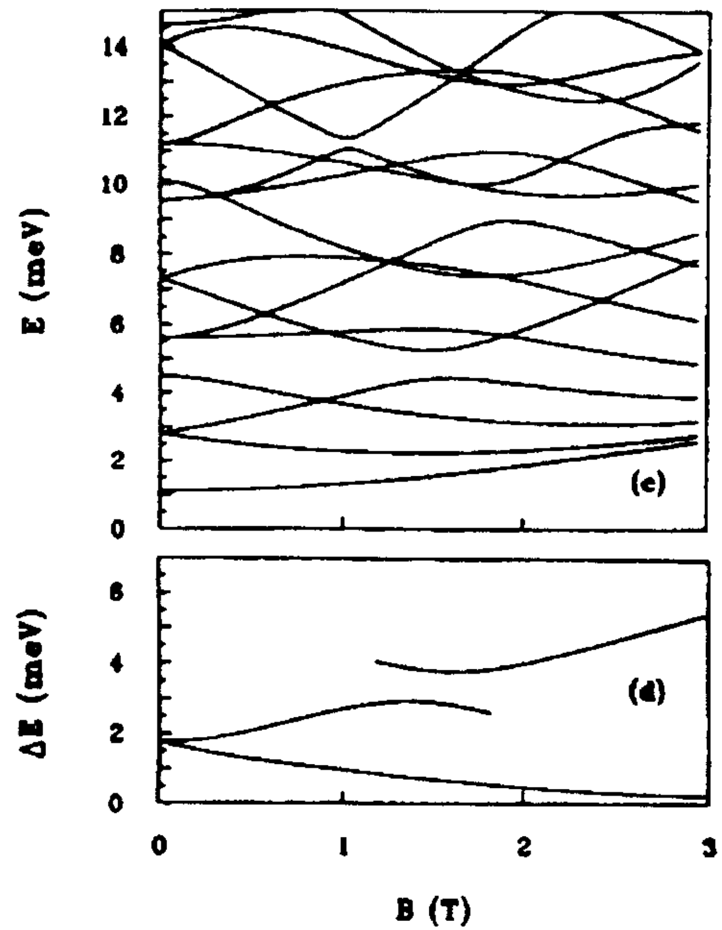
Spin-density modes and magnetoplasmons in quantum dots



$$V(r)=\frac{1}{2}m^*\Omega_0\left[(x^2+y^2)+c(x^4+y^4)\right]:$$

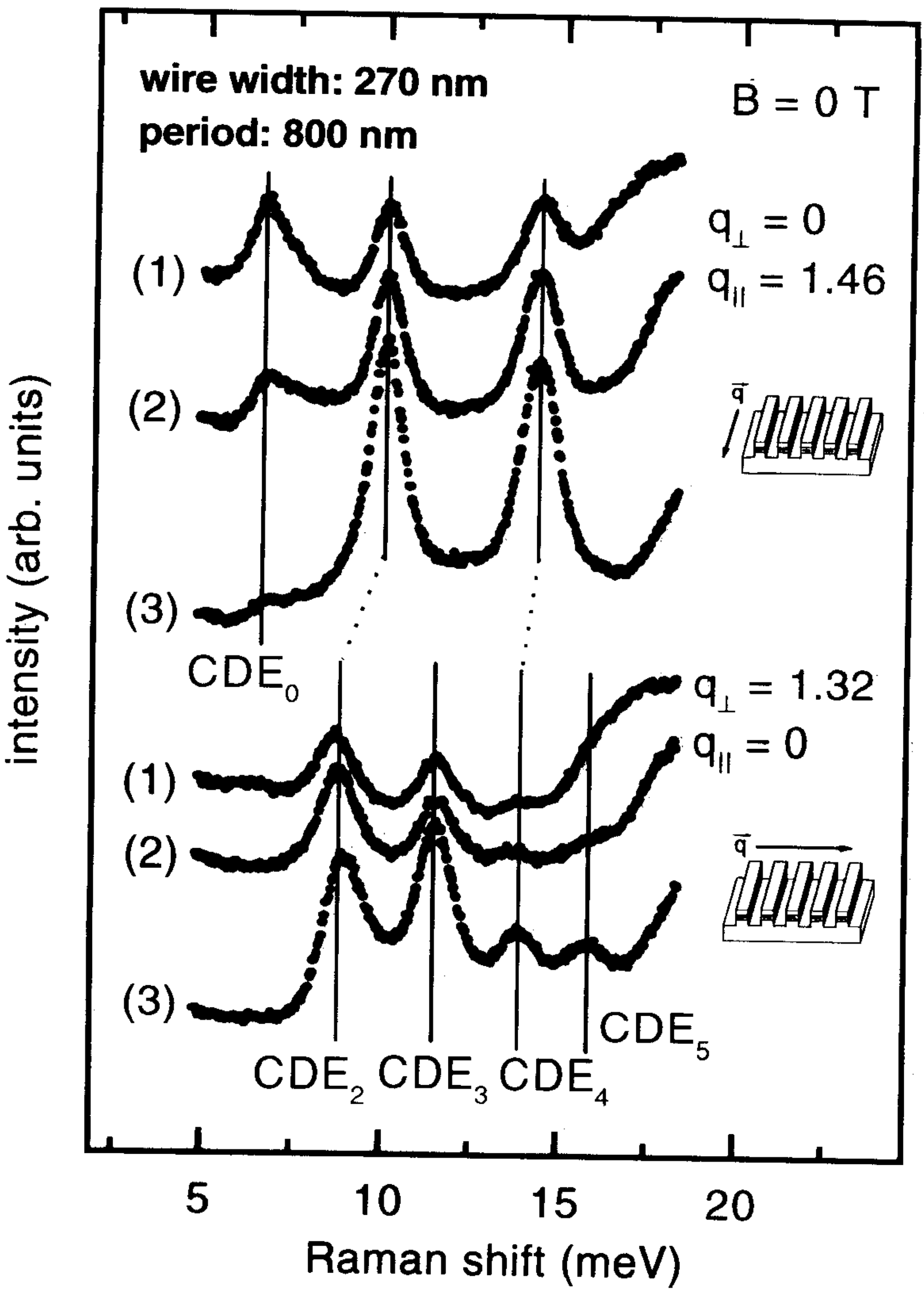


square-well potential:



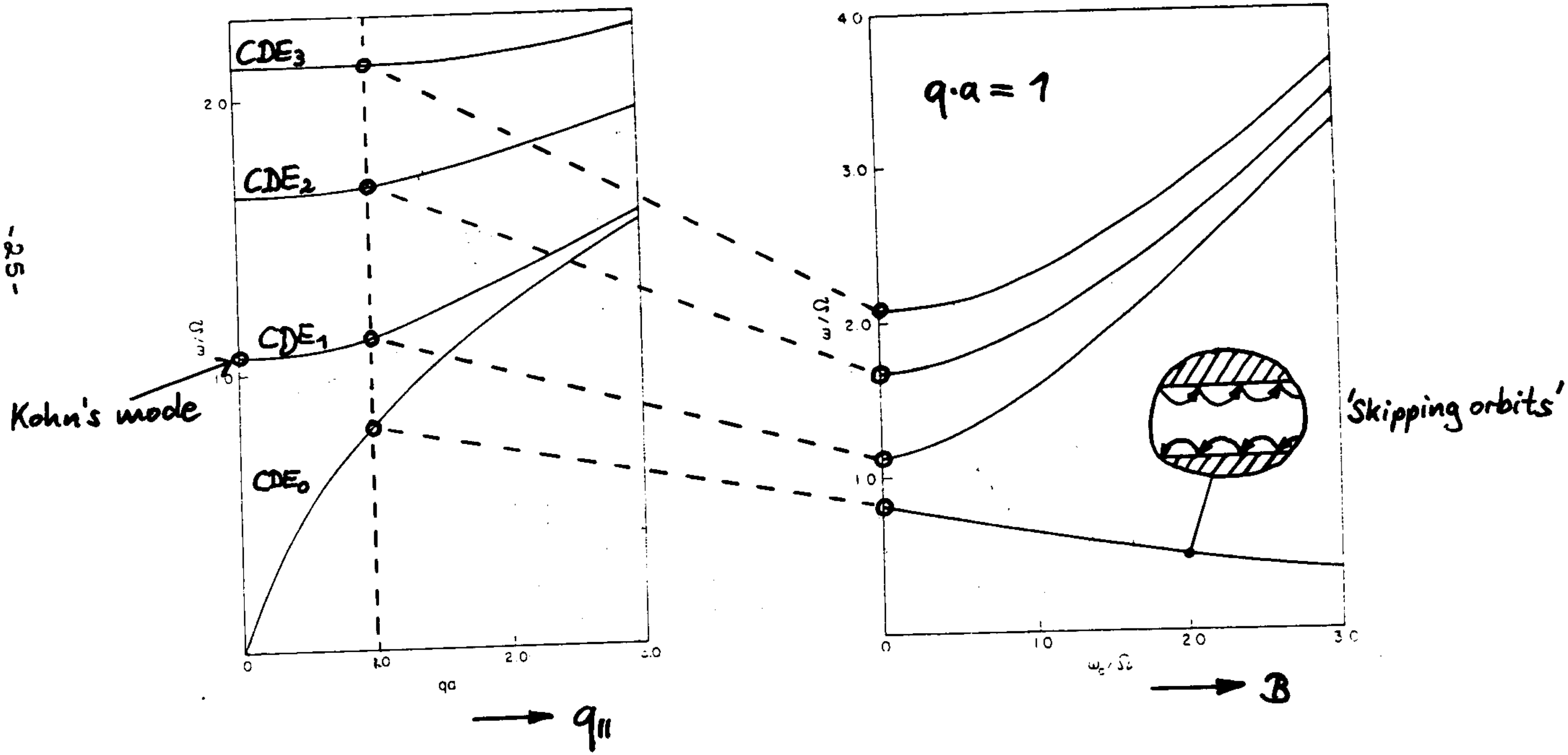
(T. Demel)

One-dimensional plasmons in quantum wires

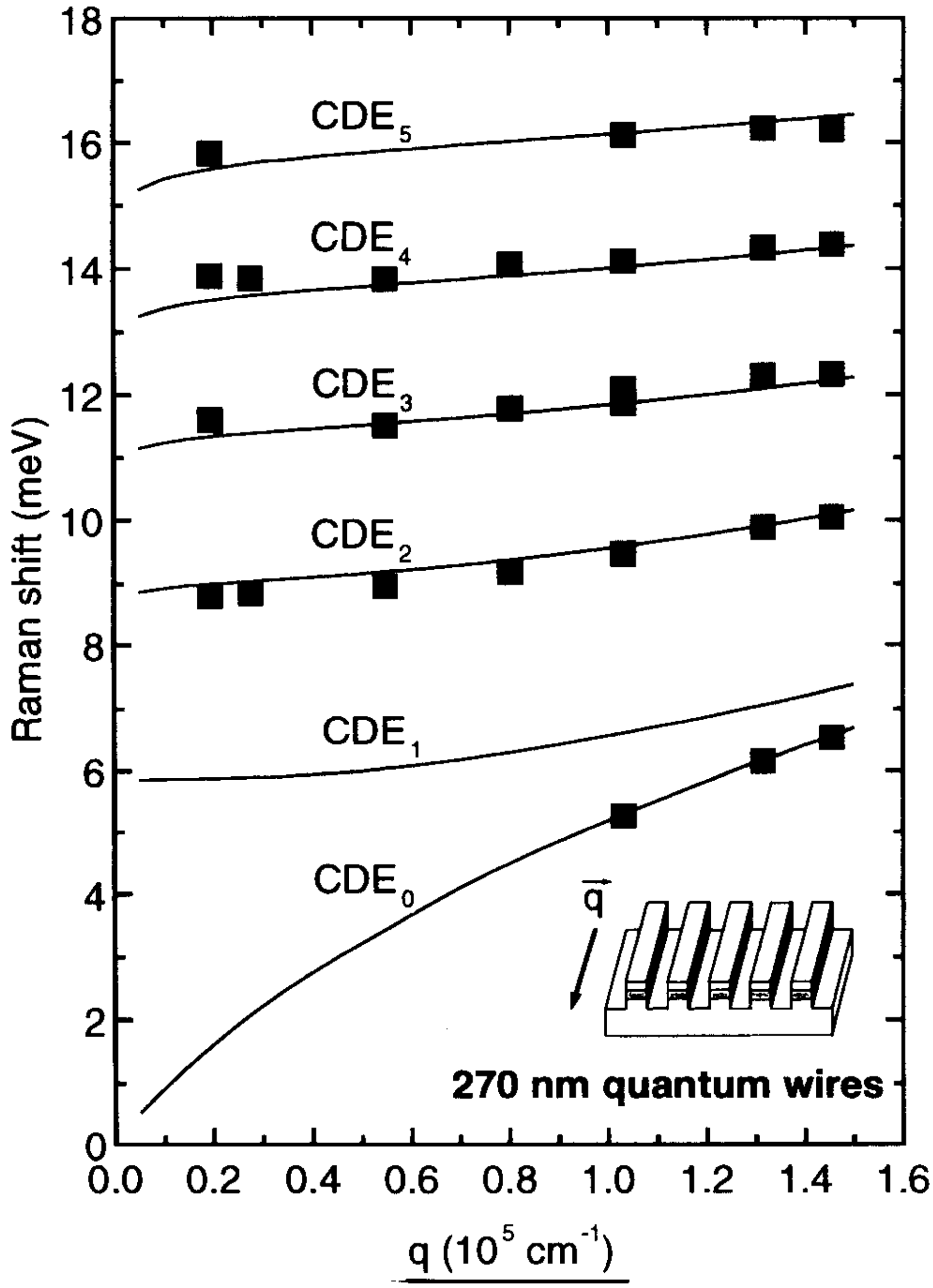


CONFINED PLASMONS

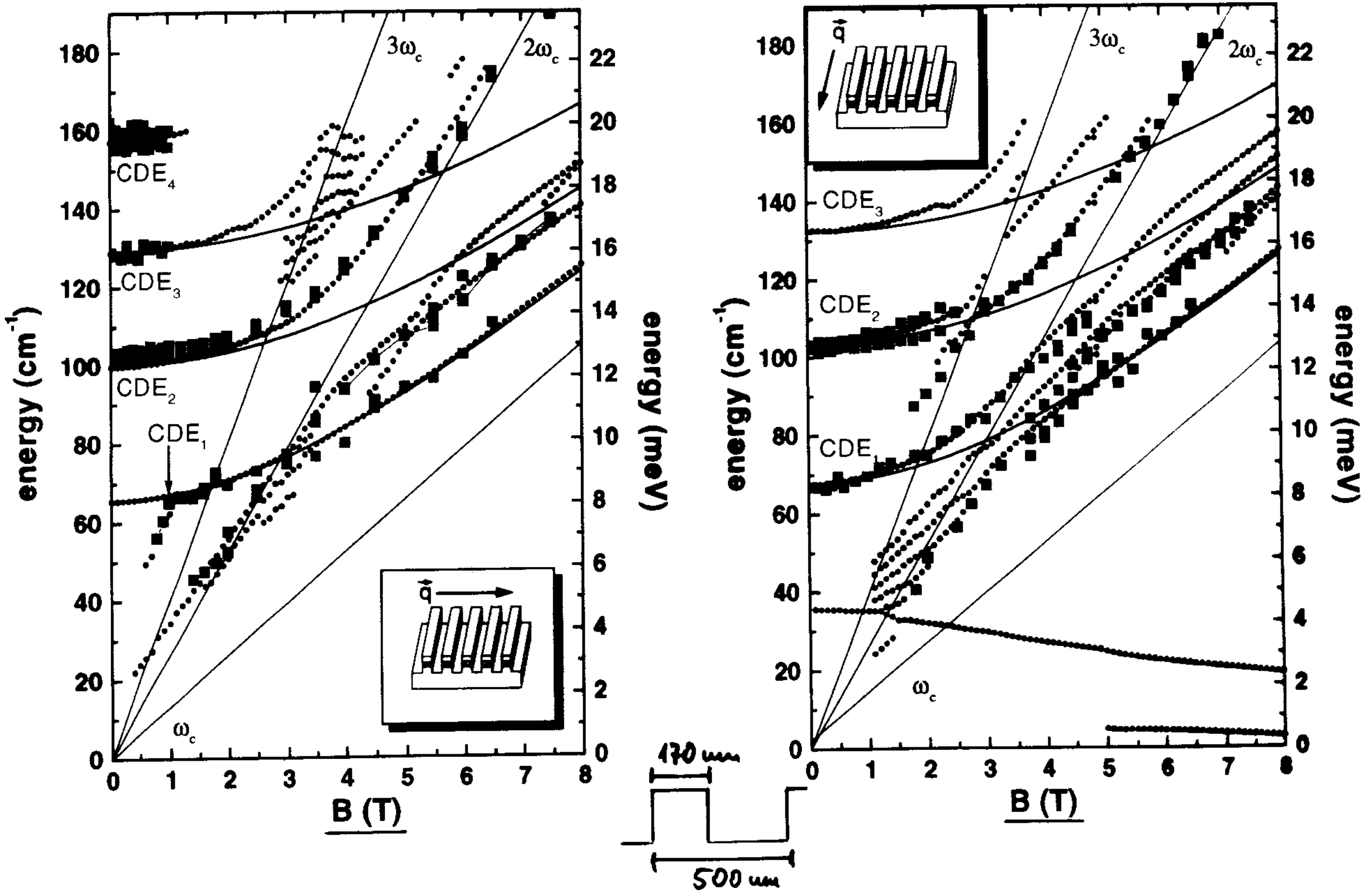
G. Eliasson et al., Solid State Commun. 60, 41 (1986) :



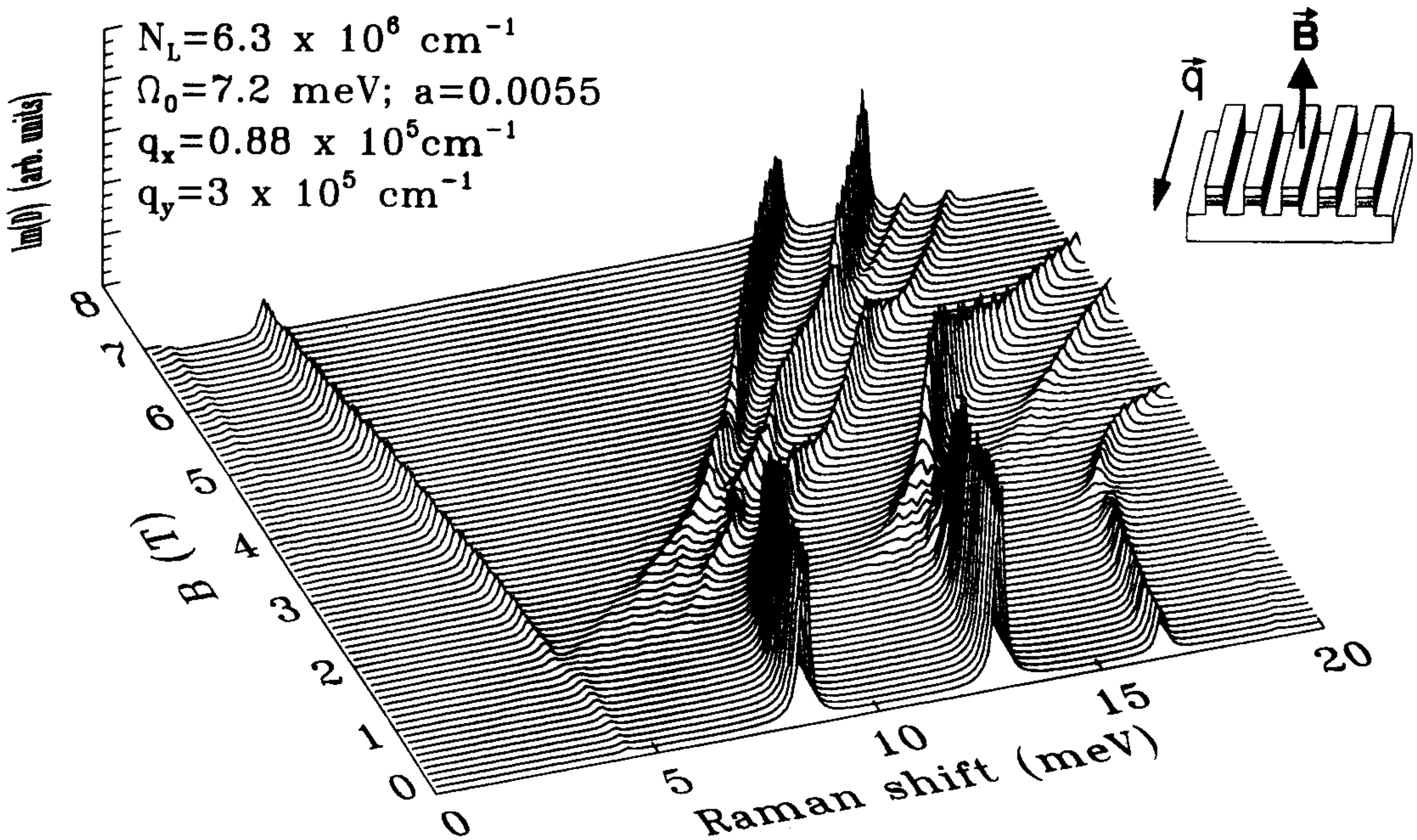
One-dimensional plasmons in quantum wires



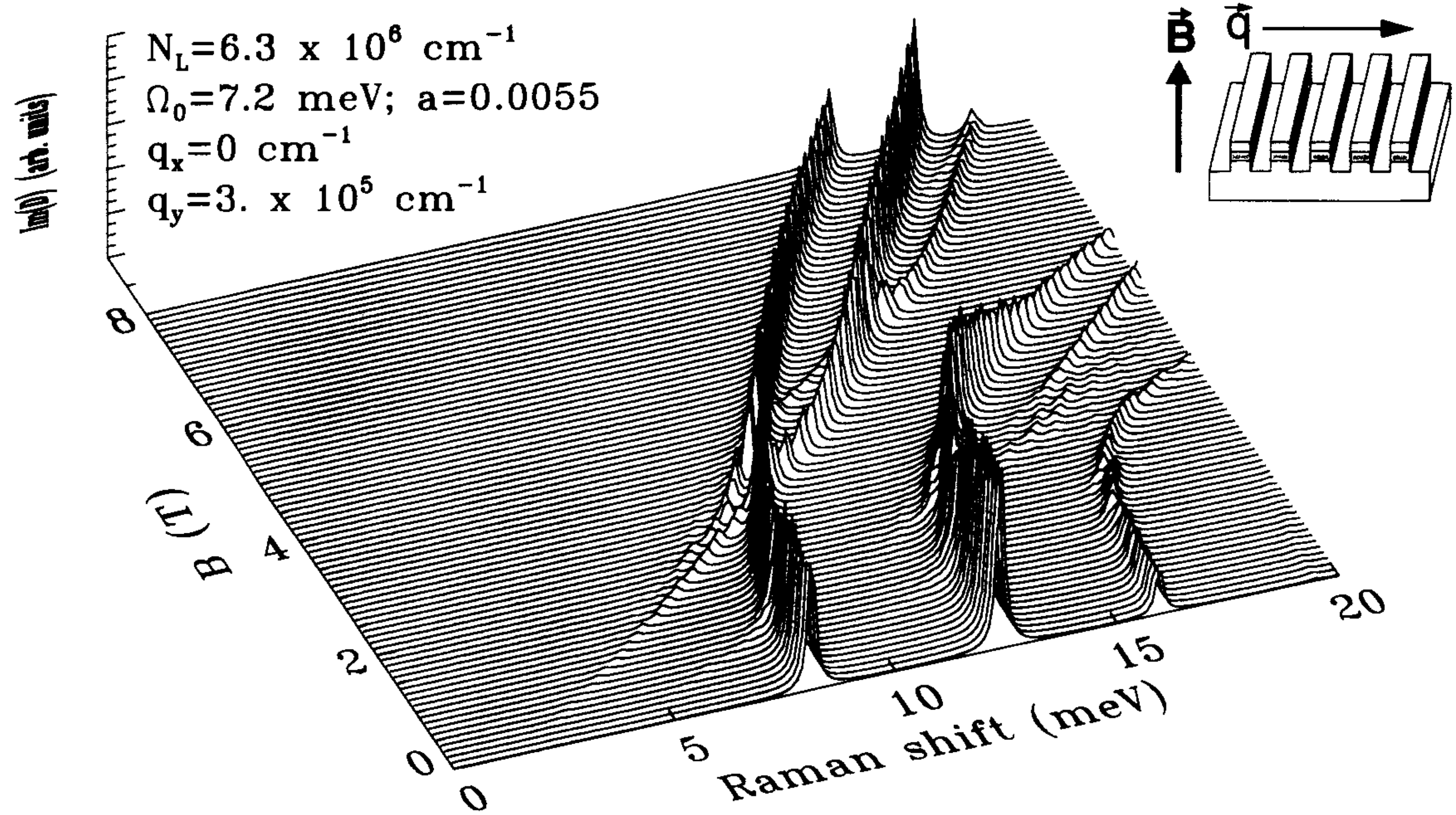
Magneto Raman scattering on 170 nm quantum wires



One-dimensional magnetoplasmons in quantum wires



Confined magnetoplasmons in quantum wires



LIGHT SCATTERING FROM ELECTRON PLASMAS IN A MAGNETIC FIELD

C. K. N. Patel and R. E. Slusher
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 23 September 1968)

We have observed Raman scattering from the hybrid plasma mode in n-GaAs and its coupling with the Bernstein modes at harmonics of the cyclotron frequency.

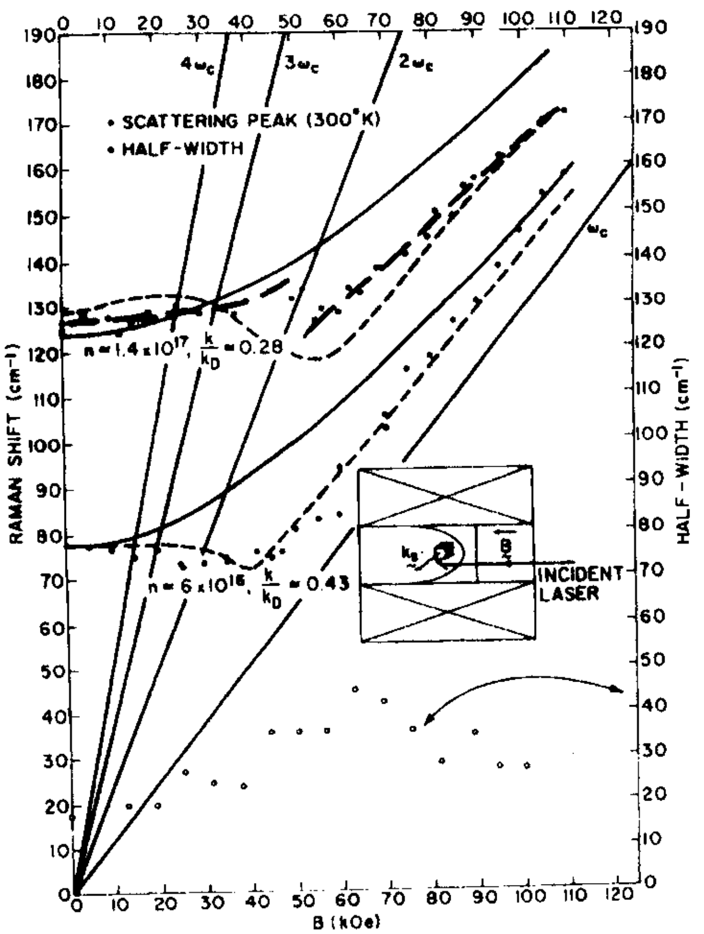
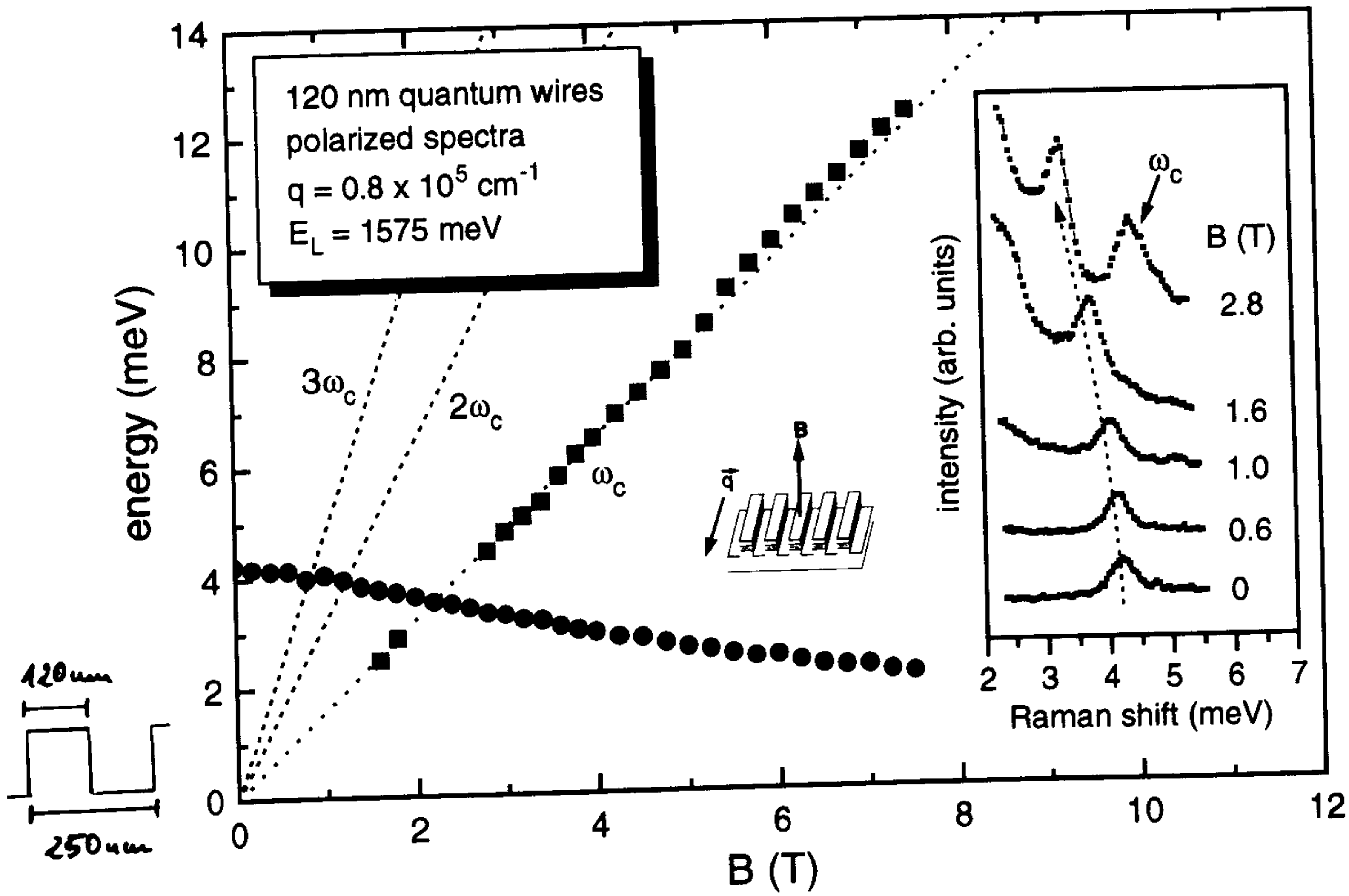


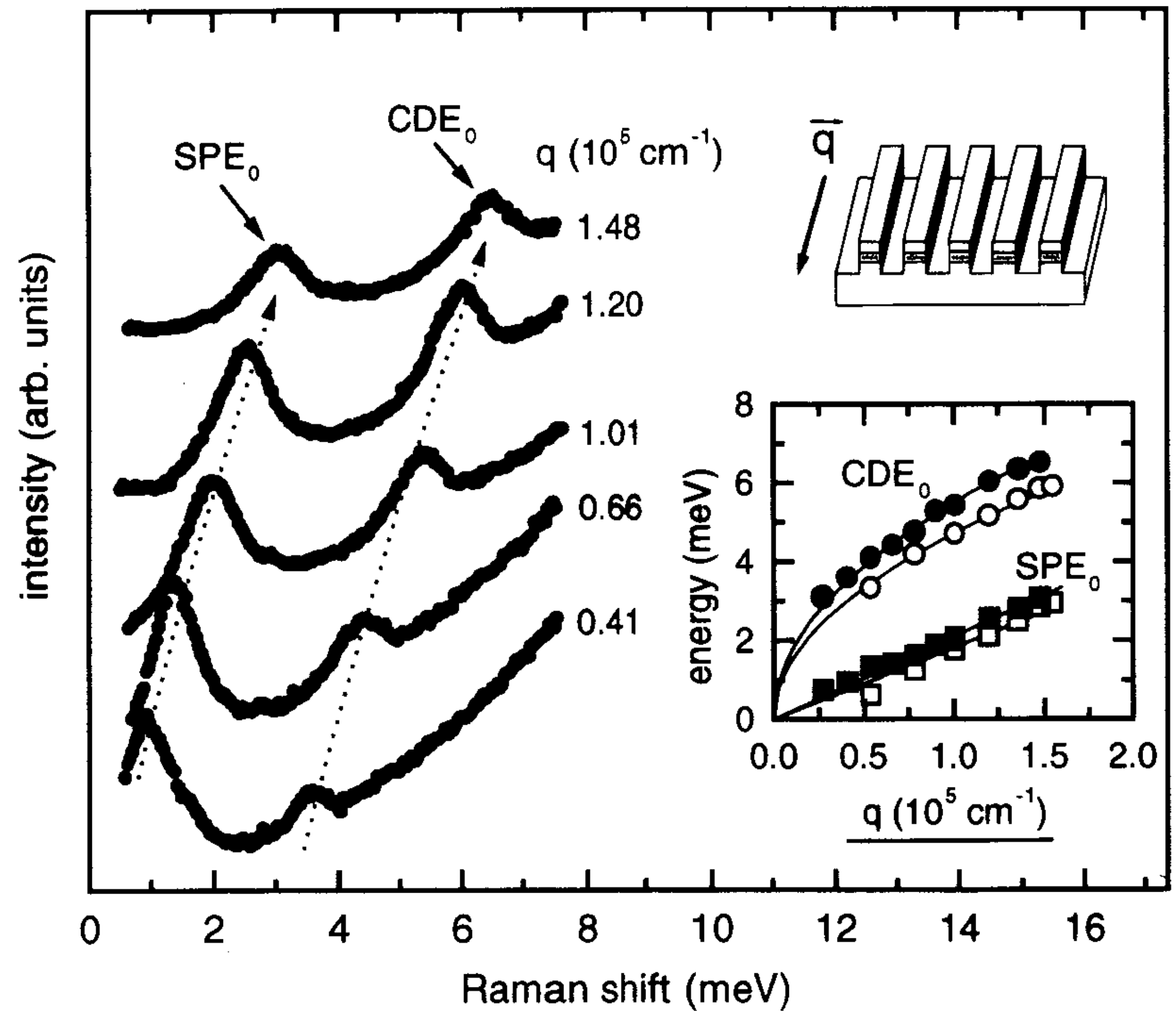
FIG. 1. Frequency shift as a function of $\vec{B}$ of inelastically scattered light with $\vec{k}\perp\vec{B}$ from coupled plasmon-cyclotron modes of electron gas in n-GaAs for three different electron densities, and half-width of the above scattered light for $n_e \approx 1.6\times10^{17}$ n-GaAs sample.

- **internal interactions in a 3D electron gas**
- **incompressibility**
- **nonlocality**

One-dimensional magnetoplasmons in quantum wires



One-dimensional plasmons in quantum wires



Summary

- We have observed a finestructure in the spectrum of spin-density excitations in quantum dots which is due to a nonparabolic lateral potential.
- The splitting of the lowest spin-density mode, the SDE_1, is interpreted, in analogy to the edge magnetoplasmon, as an *edge spin-density mode.*
- In quantum wires with small periods, we observe a one-dimensional plasmon with a negative magnetic-field dispersion due to skipping orbit motions of the individual electrons.
- Evidence for a coupling between adjacent wires is found.