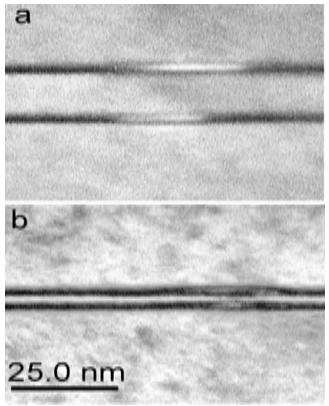
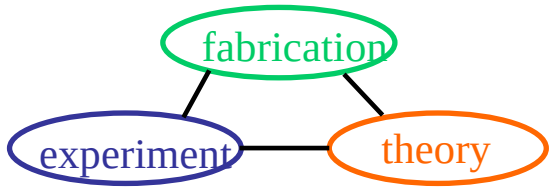
QUANTUM DOTS AND MICROCAVITIES FOR QUANTUM INFORMATION TECHNOLOGY



Tom Reinecke
Naval Research Laboratory

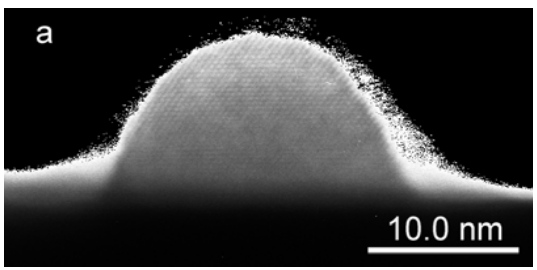


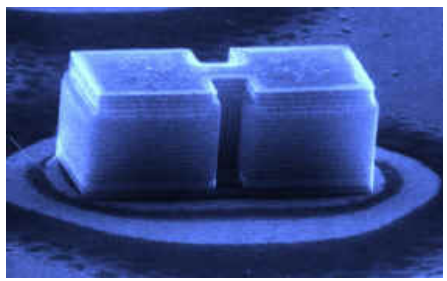
Outline
quantum dots as qu-bits
coupling of QD's for two qu-bit gates
microcavities for QD coupling

collaborators:

- *Naval Research Laboratory*: T. L. Reinecke, Y. Lyanda-Geller, L. M. Woods
- *University of Wuerzburg*: group of A. Forchel
- *University of. Dortmund:* group of M. Bayer

-- supported by DARPA and NSA





QUANTUM INFORMATION TECHNOLOGY

what: encryption, quantum communications, quantum computing

quantum computing:

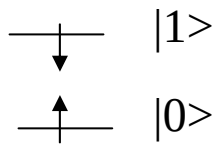
- factoring large numbers
- searching large databases
- large scale parallel
- polynomial scale with size

physical implementations of qu-bits:

- nuclear spins in liquids
- atoms in cavities
- superconducting junctions
- impurities in semiconductors
- quantum dots
- photon polarizations

--- solid state implementations needed for scalability

'qu-bit'



$$\Psi = \alpha|0\rangle + \beta|1\rangle = Ae^{i\phi}$$

quantum gate/'entanglement'

product states → to 'entangled' states

$$\Phi_p = A|0\rangle_1|1\rangle_2$$

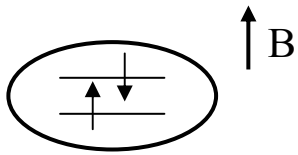
$$\Phi_e = \gamma|0\rangle_1|1\rangle_2 + \lambda|1\rangle_1|0\rangle_2$$

QU-BIT REQUIREMENTS - QUANTUM DOTS

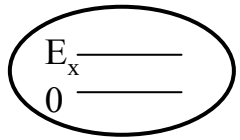
I. define two state qu-bits
II. ‘address’ single qu-bits
III. couple qu-bits for gates
IV. maintain coherence for operations

I. define two state qu-bit

spins in quantum dots



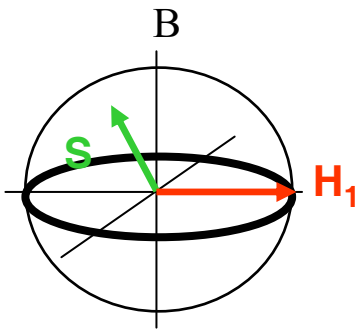
excitons in quantum dots

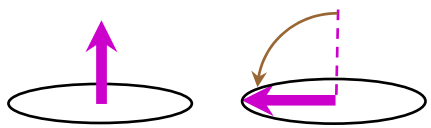


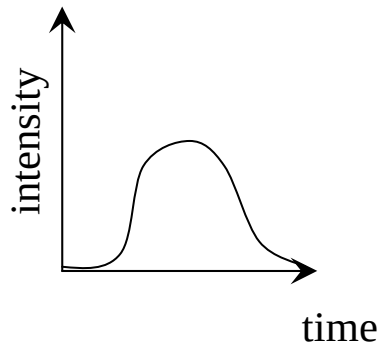
II. set arbitrary state coherently

- (rf ‘nano’-magnetic field)
- spin flip Raman pulse

- pulsed band gap laser

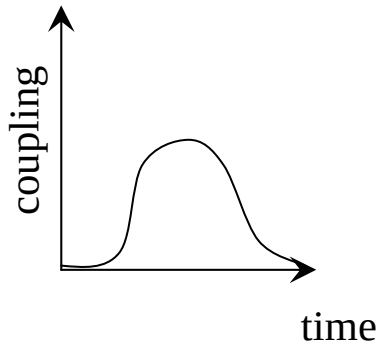






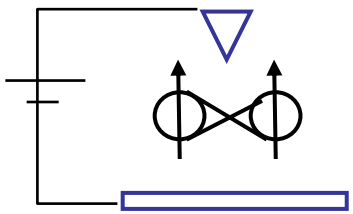
REQUIREMENTS OF PHYSICAL IMPLEMENTATIONS – QUANTUM DOTS

III. couple qu-bits coherently for gates

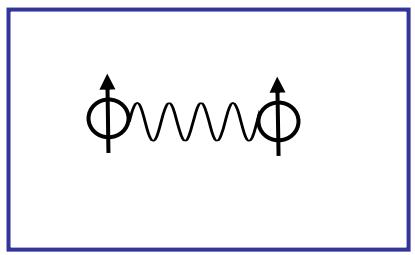


possibilities discussed for dots

'nanogates' to control wavefunction overlap



photon exchange in microcavity



coupling between qu-bits most challenging for physical implementations

NANOSTRUCTURES AND QUANTUM INFORMATION

quantum information uses full analog wavefunction as ‘qu-bit’

$$\Psi = \alpha|0\rangle + \beta|1\rangle = Ae^{i\phi}$$

—— |1>

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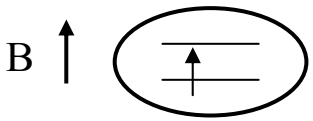
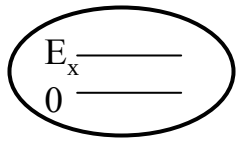
- solid state implementations sought for scalability and integration
- decoherence often a problem

I. physical implementations for qu-bits:

spins in quantum dots



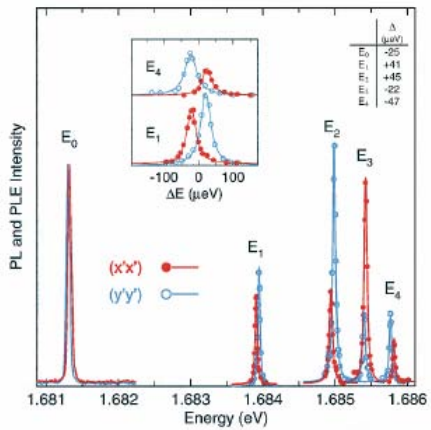
excitons in quantum dots



II. physical implementations for quantum gates:

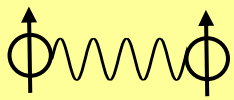
directly coupled

cavity coupled



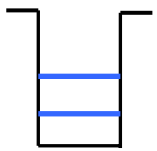
want controllable ‘entanglement’ of states of two qu-bits

$$\Phi = \gamma|0\rangle_1|1\rangle_2 + \lambda|1\rangle_1|0\rangle_2$$

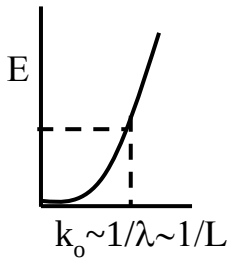
- single dot qu-bits
- coupled of dots
- microcavity coupling 

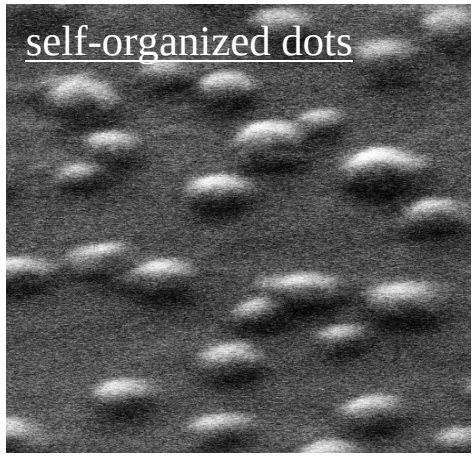
QUANTUM DOTS

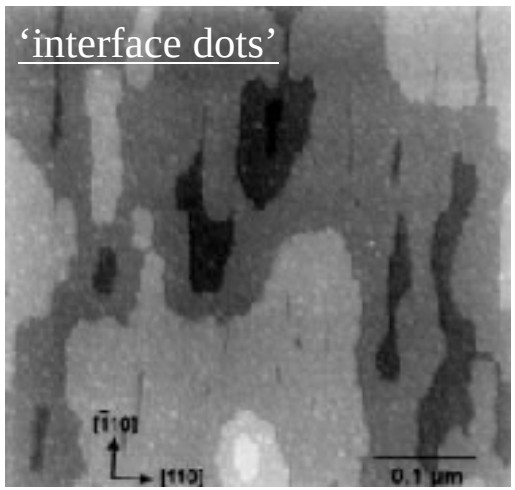
‘artificial atoms’

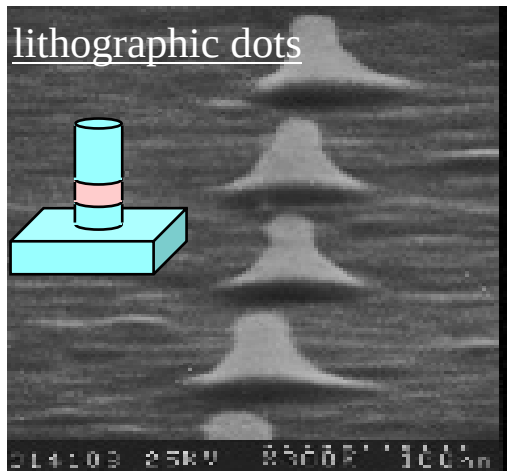


$$k = \frac{2\pi}{\lambda}$$





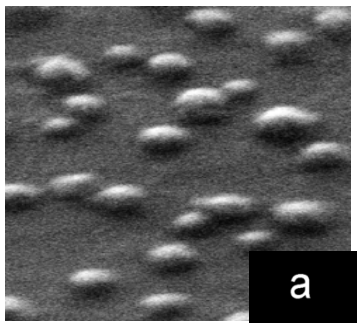


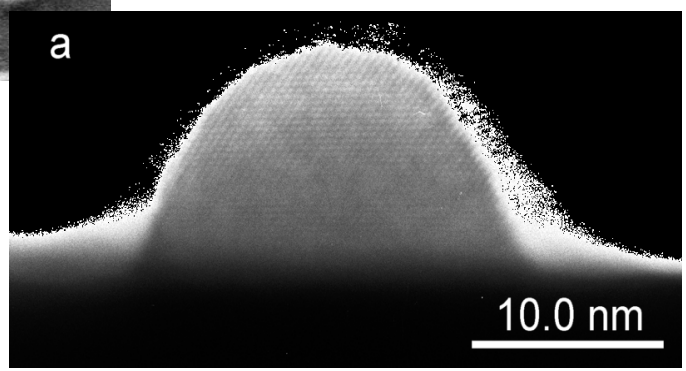


SINGLE SELF ASSEMBLED QUANTUM DOTS

- Stranski-Krastanov InAs and $In_{0.6}Ga_{0.4}As$/GaAs dots grown by MBE
- doping of spins into dots

GaAs cap layer	100 nm
$In_{0.6}Ga_{0.4}As$ - QDs	4.8 ML
GaAs	20 nm
GaAs (Si: $2x10^{18}$)	10 nm
GaAs buffer layer	120 nm
undoped GaAs substrate	500 µm

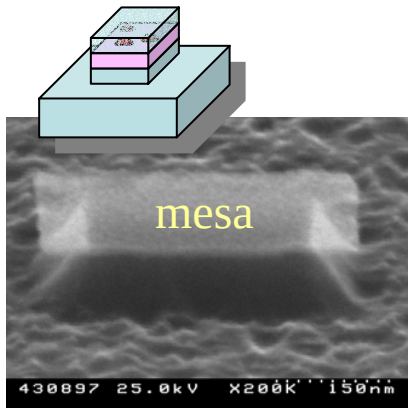


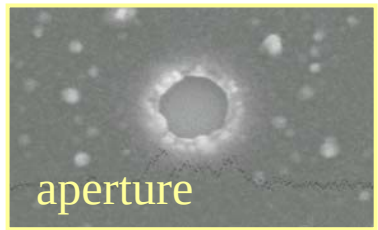


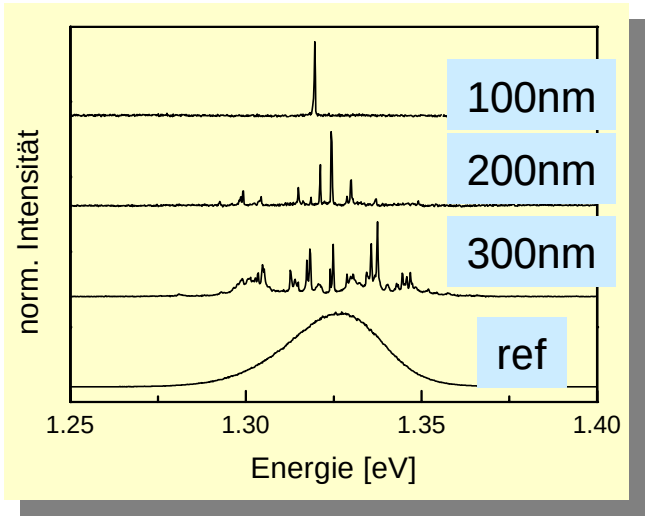
microscopy: J.P. McCaffery, NRC Canada

single dot spectroscopy

insolated by lithography for optical studies

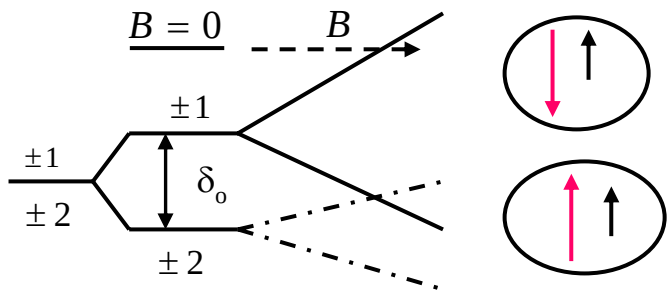




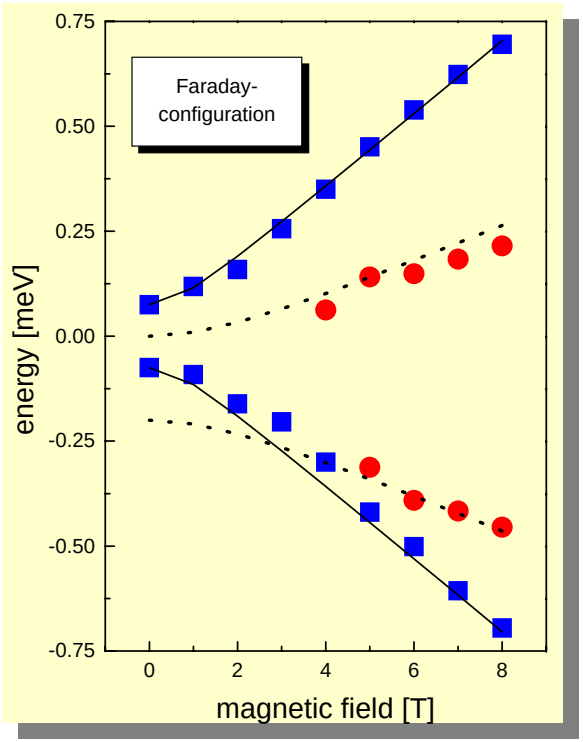


EXCITON FINE STRUCTURE IN QD's

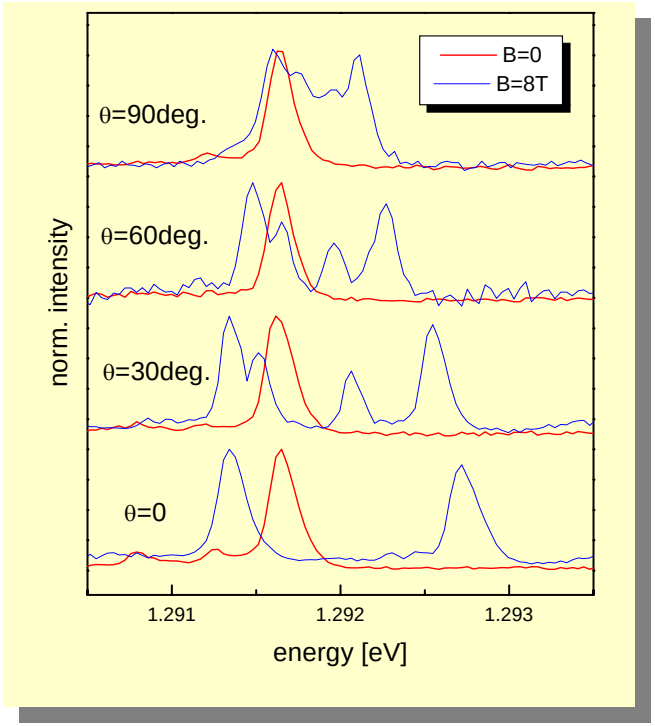
- sharp lines as potential qu-bits
- fine structure given by exciton spins couples to light in coherent optical control
- we have done extensive work done on optical properties e.g., *PRL* ***82***, *1748 (1999); PRB* ***65***, *195315 (2002)*



example: InGaAs QD's with lowered symmetry



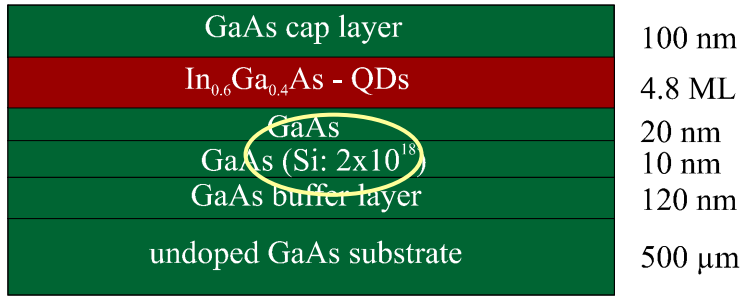
example: controlled access to dark states with tilted fields



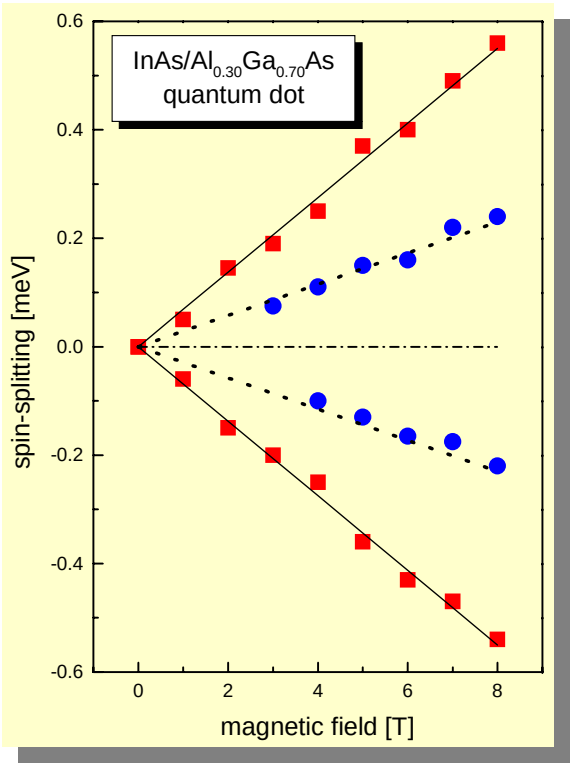
SPIN DOPED QUANTUM DOTS

- for qu-bits
- have done extensive work done on optical properties of trions e.g., *PRL* ***82****, 1748 (1999); PRB 65, 195315 (2002)*

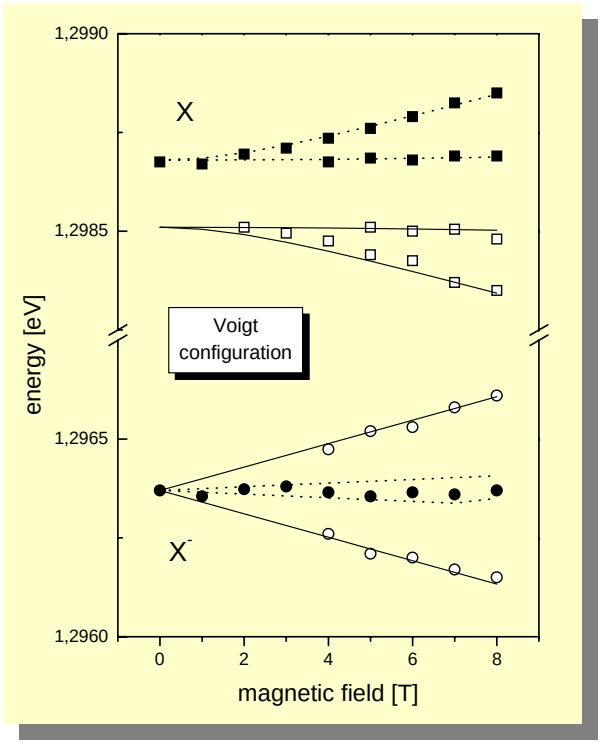
spins doped into QD's in growth

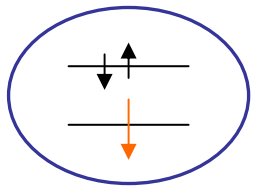


Faraday configuration



Voigt configuration



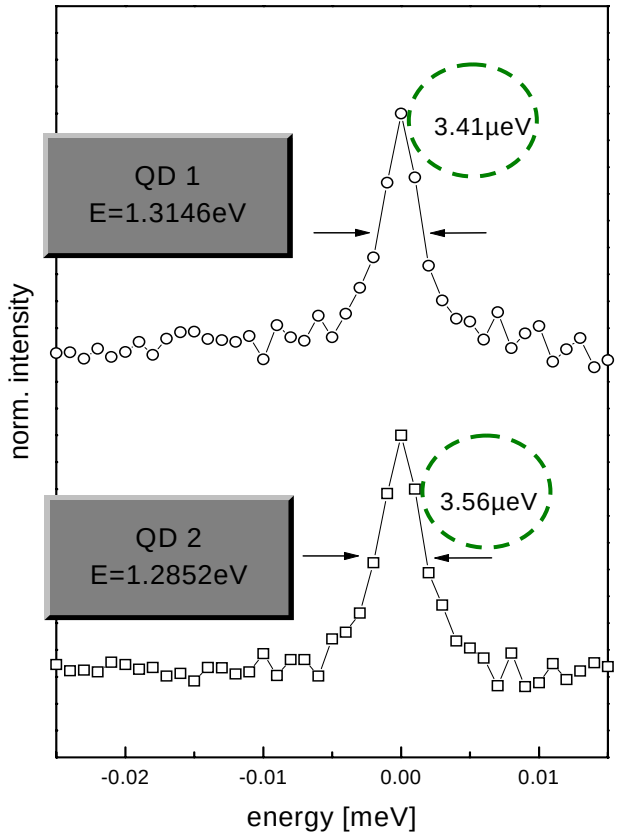


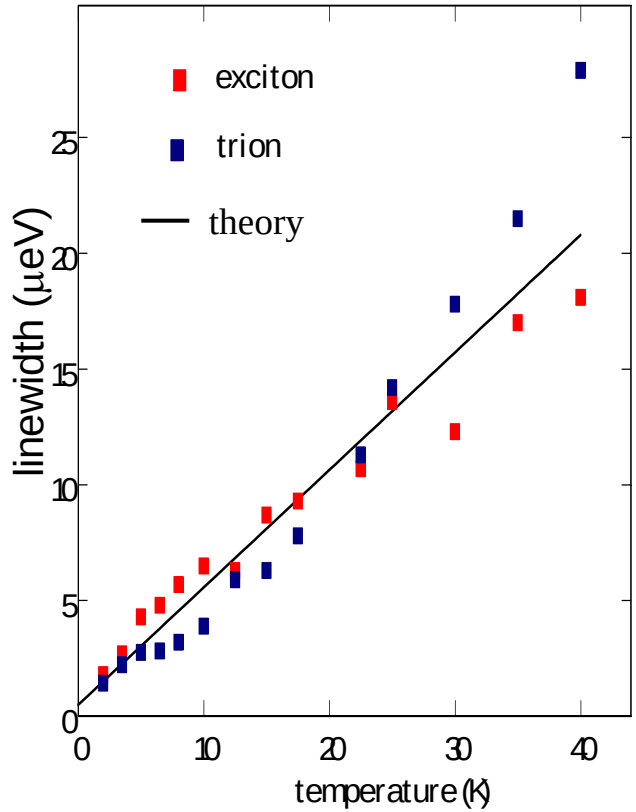
trion signature:

- no exchange energy
- spin of trion from hole
- symmetric spin splittings

EXCITON, TRION DEPHASING IN SINGLE DOTS

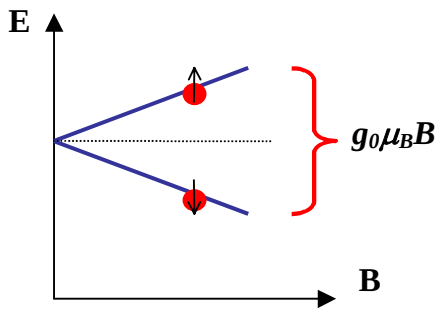
- resonant excitation and PL for homogeneous linewidths
- single $In_{0.6}Ga_{0.4}As/GaAs$ QD's with mesas
- ultranarrow lines < 3.5 μeV
- T_2 ~ 1 nsec at 2K limited by emission
- linear T dependence different from bulk - consistent with theory from phonon scattering



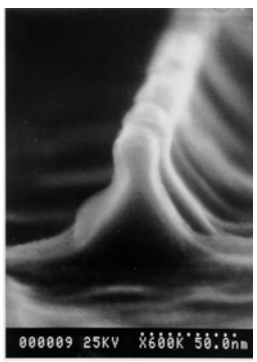


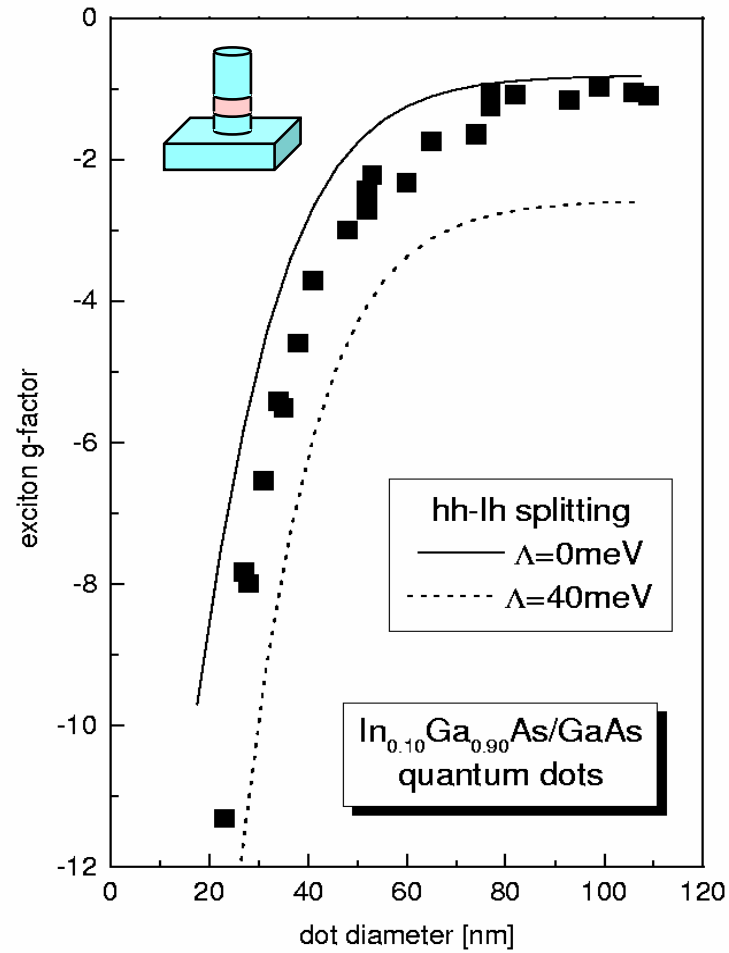
ENHANCED SPIN SPLITTINGS IN DOTS

large spin splittings needed for thermal stability



$H_s \sim g\mu_B B\hat{s}$ s= ↓ ↑ $s = \pm\frac{1}{2}$

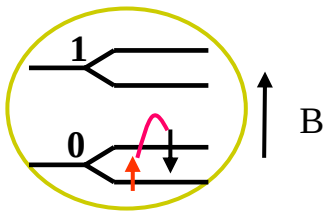


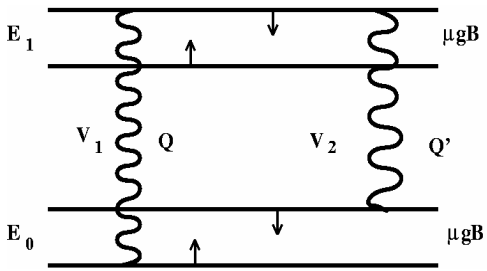


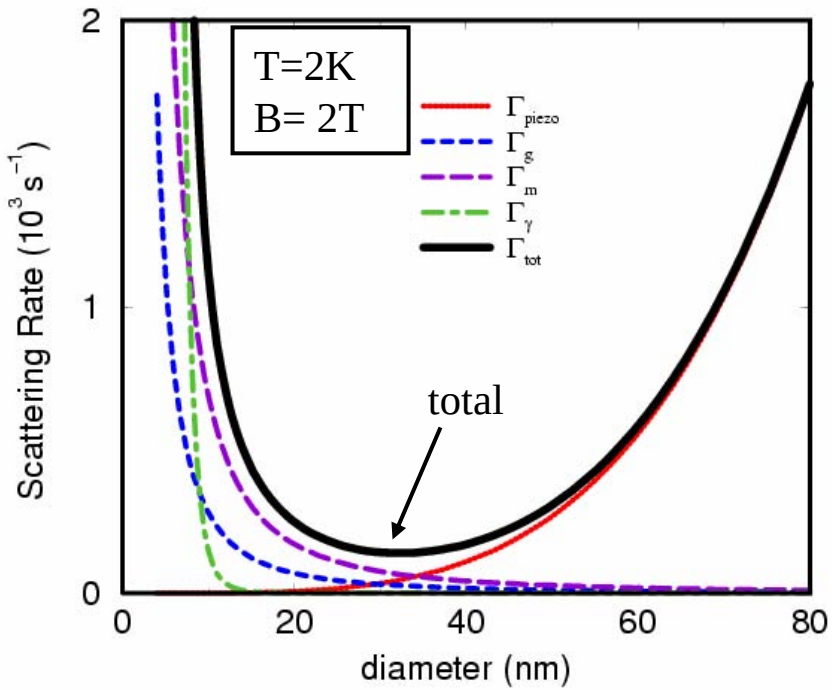
- deep etched InGaAs/GaAs system
- spin splittings enhanced over bulk x20, the largest known

DEPHASING OF SPIN IN QD

- single spin dephasing in B in QD of critical interest
- few experiments, difficult to interpretation
- developed microscopic theory of intrinsic low T spin dephasing
- from phonons mediated by spin orbit interaction
- critical role of new interface phonon coupling



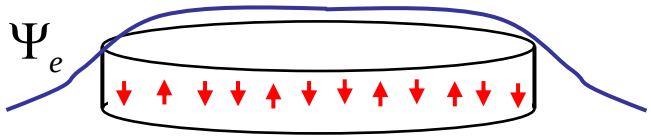




- InGaAs self-organized QD's
- intrinsic rates in dots slow ~ 10^{-3} sec^{-1}
- strong increases with ~T^{11} and ~B^5
- consistent with early experimental estimates < 200 μsec (Fujusawa, 2002)
- find dependences on system
- minimum for size ~ self organized dots

- spin dephasing time due to phonons in QD can be very long

ELECTRON SPIN 'DEPHASING' IN QD ~ 0.1 μsec



main spin 'dephasing' is from inhomogeneous hyperfine coupling to ~ 10^5 nuclei

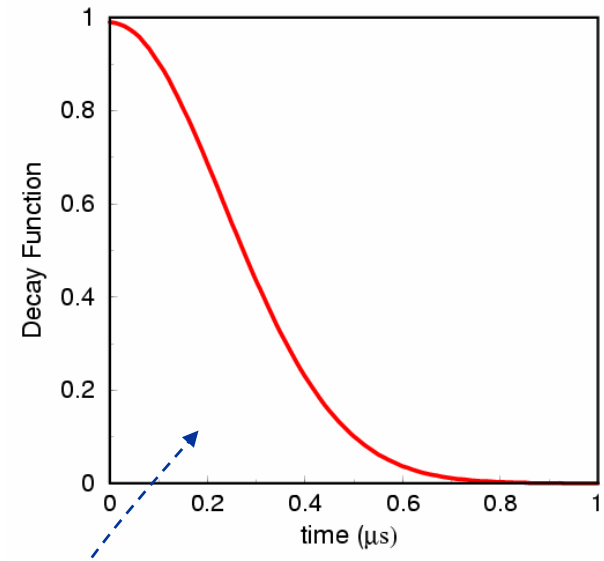
$$H = \vec{S} \bullet \sum_i A_i(r)\vec{I}_i$$

- secular sharing of spin between electron and nuclei gives effect of dephasing
- dipolar nuclear spin diffusion ~ 10^{-4} sec
- electron dephasing by phonons ~ 10^{-3} -10^{-6} sec
- first quantitative results for realistic systems

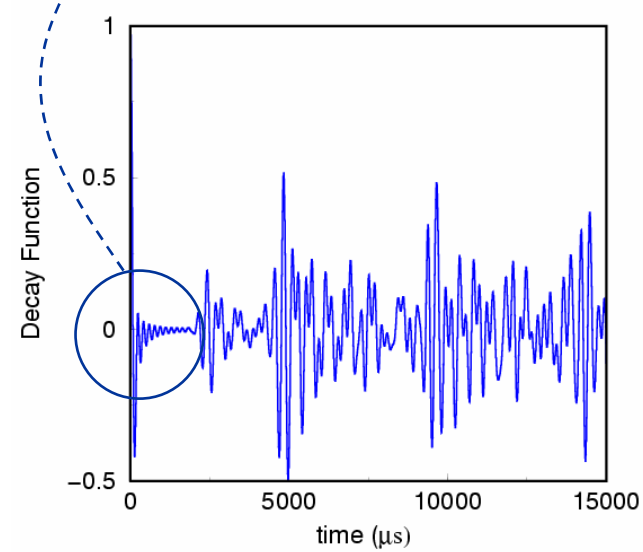
$$T_1 \sim (\text{oscill fn}) + (\text{oscill fn}) \times (\underline{\text{decay fn}})$$

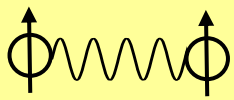
- polarized nuclei – slower 'decay'
- depolarized nuclei – simple decay
- of possible interest for storage

90% polarized nuclei

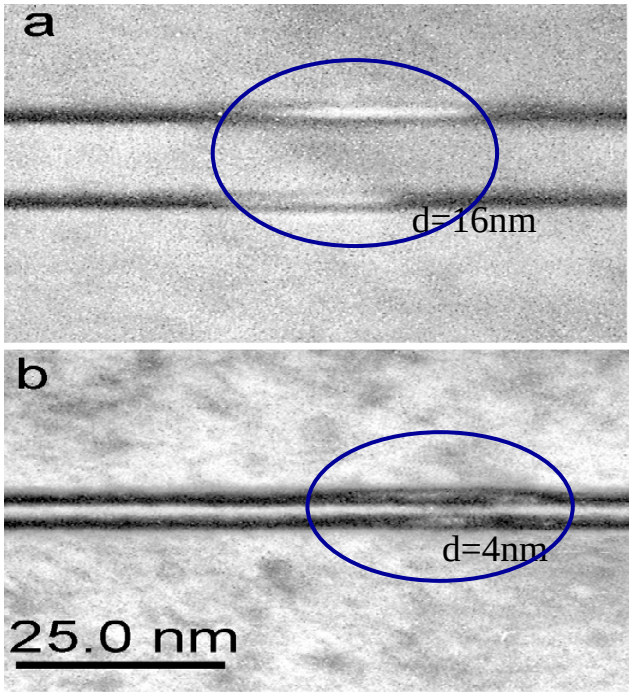


100% polarized nuclei



- single dot qu-bits
- coupled of dots
- microcavity coupling 

VERTICALLY COUPLED QUANTUM DOTS

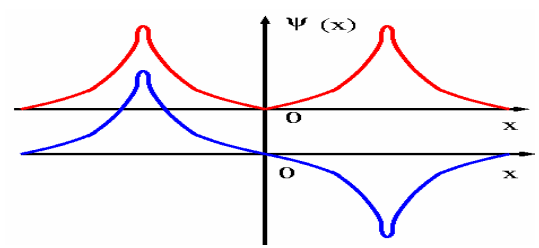


samples: NRC Canada

- vertically coupled self organized InGaAs/GaAs (Wuerzburg) and InAs/GaAs (NRC) grown by MBE
- alignment controlled by strains
- barriers width varied

typical electronic binding

symmetric

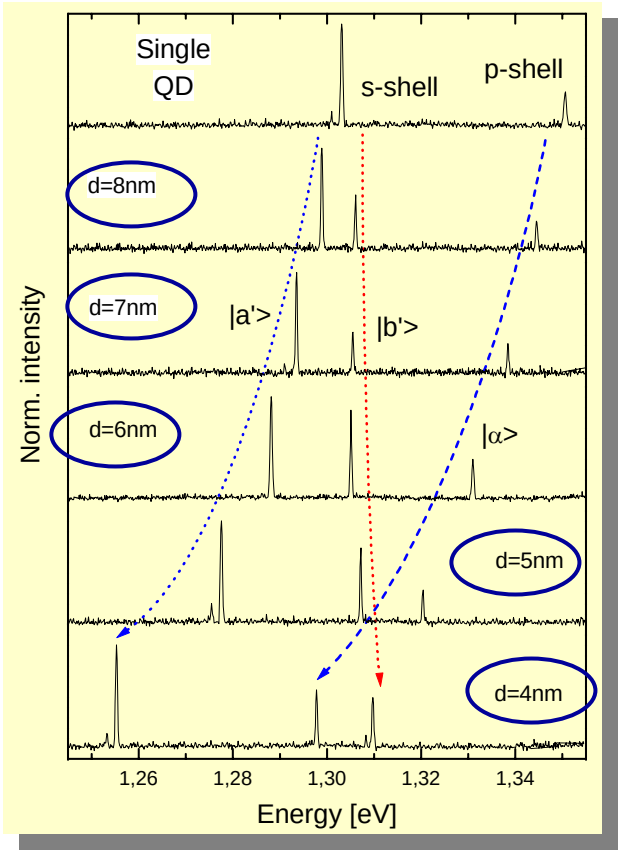


antisymmetric

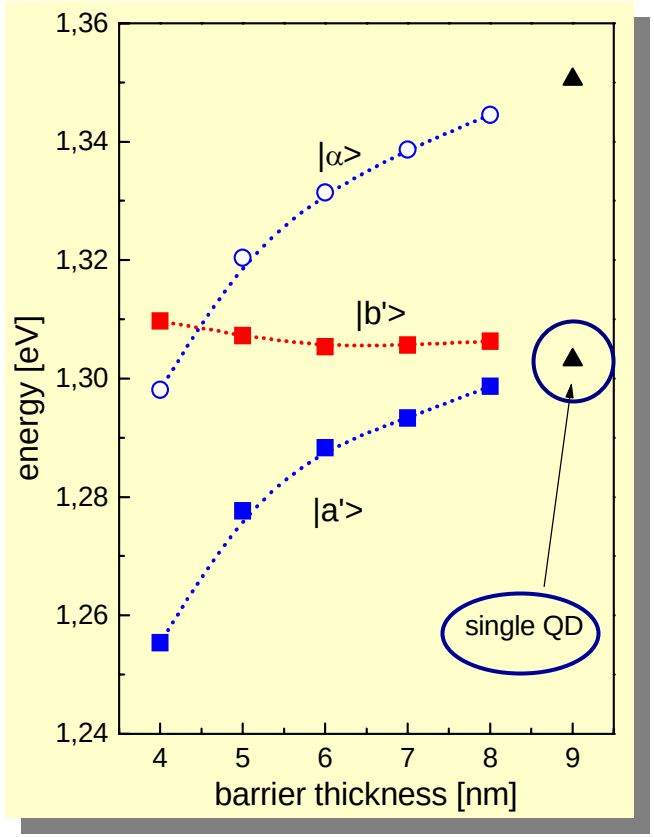
- coherent coupling
- control of coupling
- two qu-bit gates

COUPLED QUANTUM DOTS

PL vs sep'n: single InAs 'molecules'

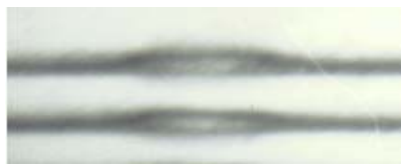


energies vs separation for InAs dots



splitting increases for decreasing dot separation

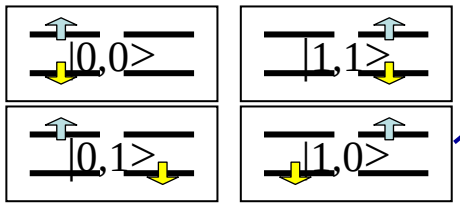
structures

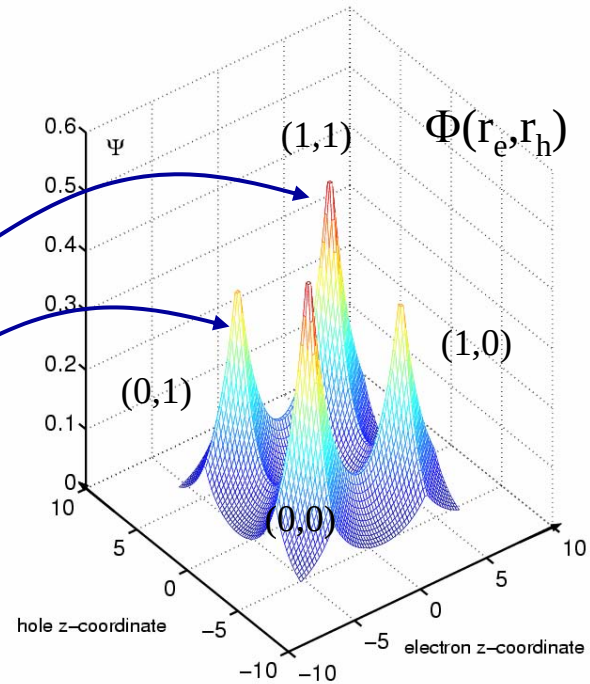


- energies split suggesting symmetric/antisymmetric states
- maximum splitting ~ 30 meV, enough to be stable at room T

ENTANGLED EXCITON STATES

- coupling of QD excitons controlled by
  - e, h tunneling
  - Coulomb interactions
- developed detailed microscopic treatment
- basis representation:

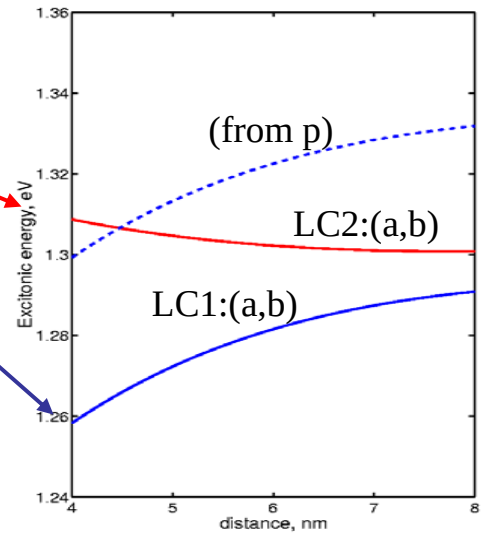




with e,h tunneling from QD s-state

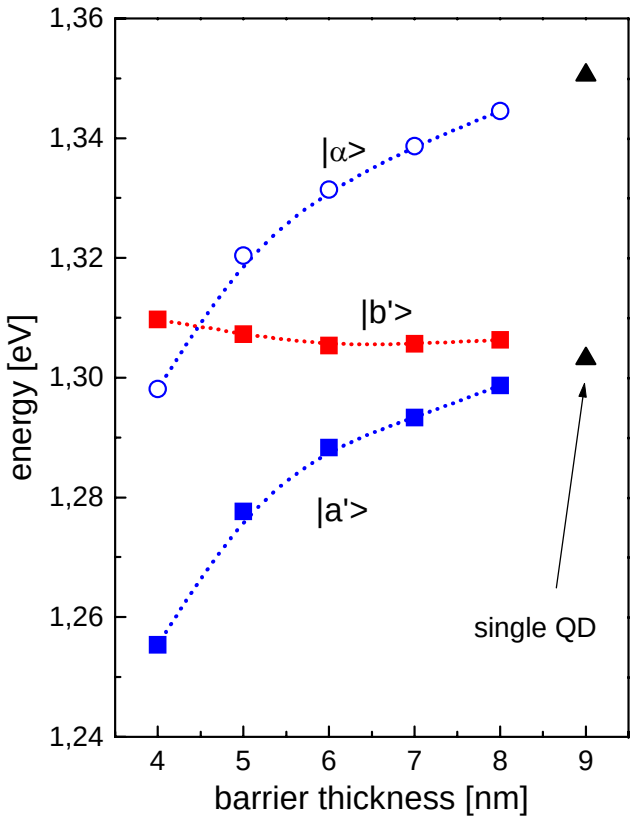
$$\begin{bmatrix} |a\rangle \\ |b\rangle \\ |c\rangle \\ |d\rangle \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} |0,0\rangle + |1,1\rangle \\ |0,1\rangle + |1,0\rangle \\ |0,0\rangle - |1,1\rangle \\ |0,1\rangle - |1,0\rangle \end{bmatrix}$$

optically active

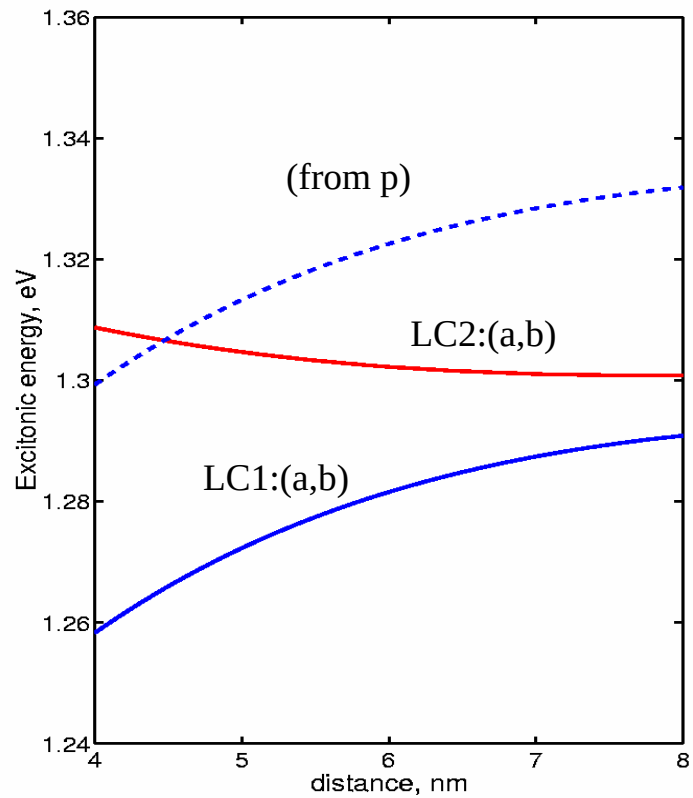


COMPARISON

experiment



calculations



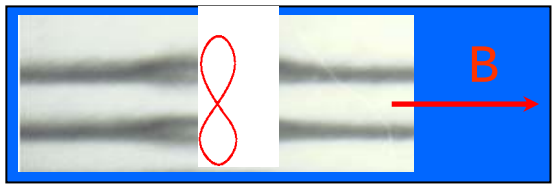
good agreement between experiment and theory with coherent quantum states

supports coherent quantum coupling

(Science **291**, 451 (2001))

DIAMAGNETIC SHIFT FOR COUPLED DOTS

diamagnetic shift in Voigt geometry

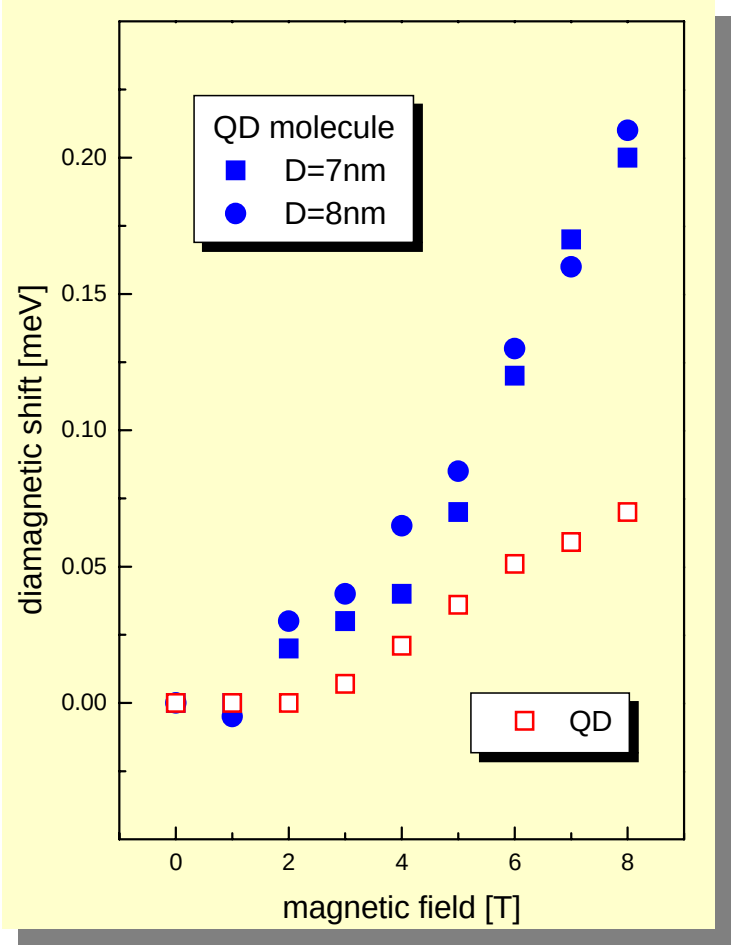


diamagnetic shift measures size of quantum wavefunction perpendicular to field

$$\Delta E = \gamma \cdot B^2$$

$$\gamma \sim \frac{e^2}{2}\left(\frac{\langle z_e^2 \rangle}{m_e} + \frac{\langle z_h^2 \rangle}{m_h}\right)$$

γ larger for molecule than for dot implies quantum wavefunction extends over molecule

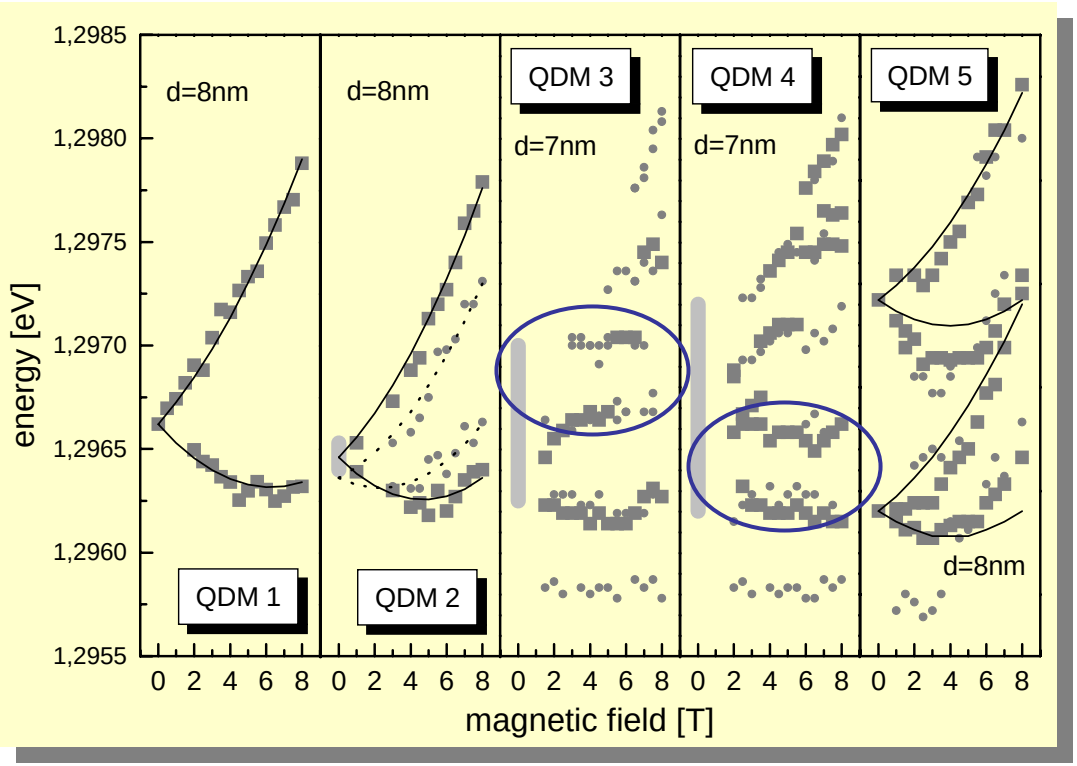


further evidence of coherent quantum coupling

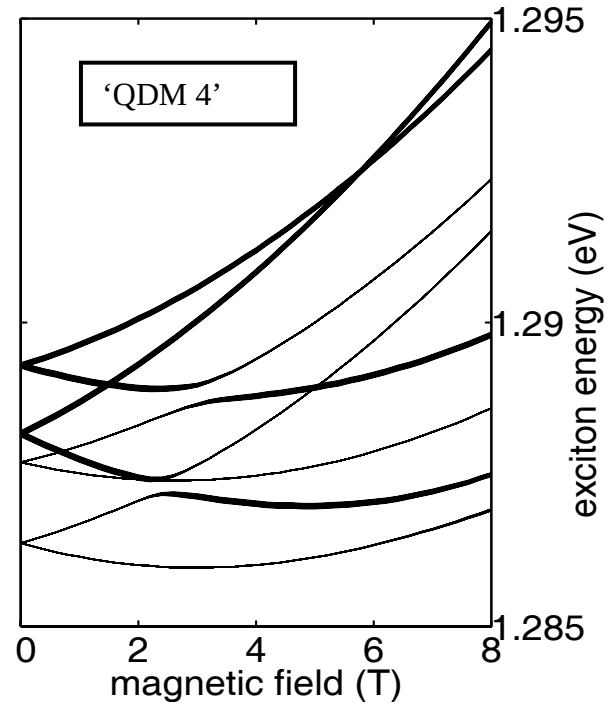
coupling

DIRECT EVIDENCE OF COUPLINGS

experiment for several molecules

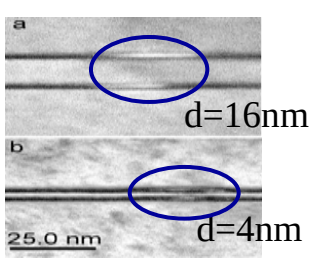


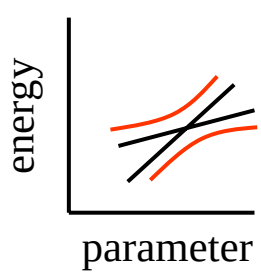
theory

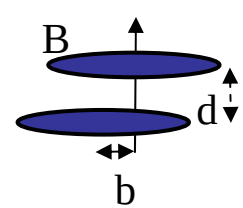


- dots have different sizes, shapes, symmetries
- anti-crossings between states from two dots

- microscopic interpretations
- from detailed fine structure
- anticrossings from deviations from symmetry





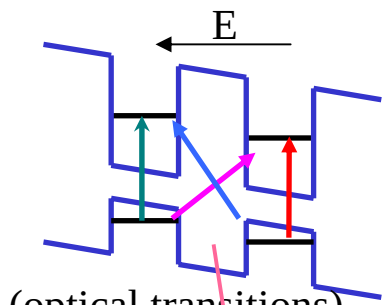


(PRL **90,** 6404 (1997))

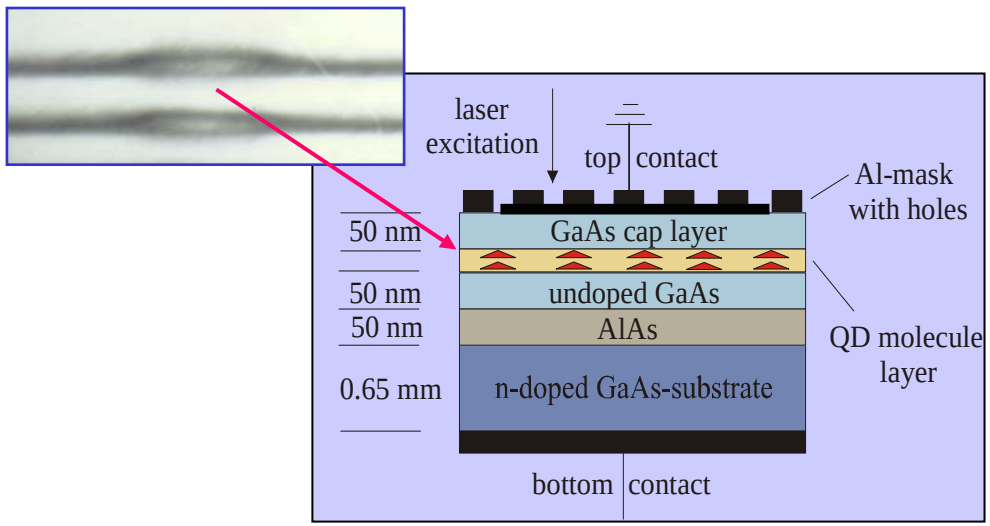
evidence of coherent quantum coupling

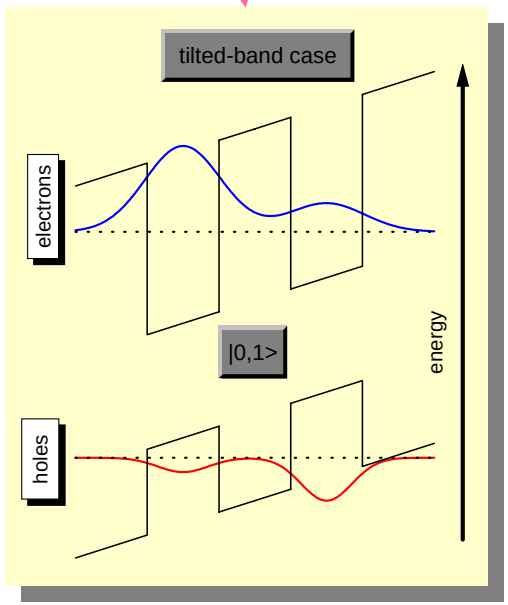
E-FIELD CONTROL OF COUPLINGS

- controlled coupling for two-qu bit gates
- seek to control interaction with one simple gate
- other proposals often require demanding nanometer fabrication



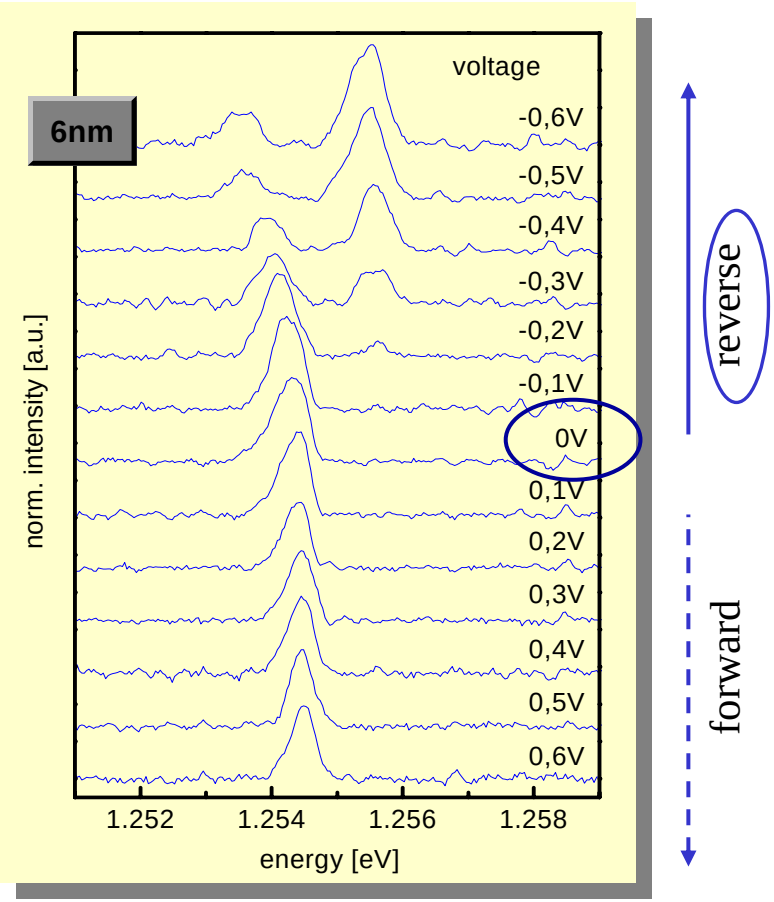
(optical transitions)





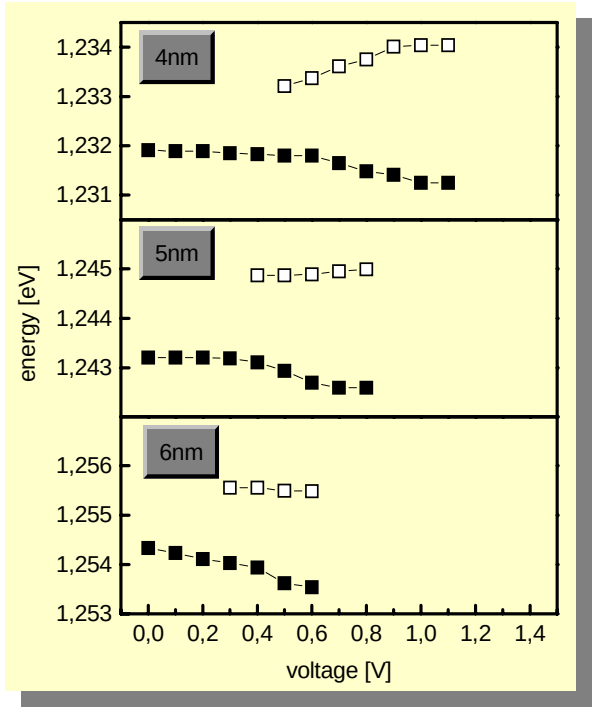
RESULTS FOR E-FIELD

E-field control of coupling



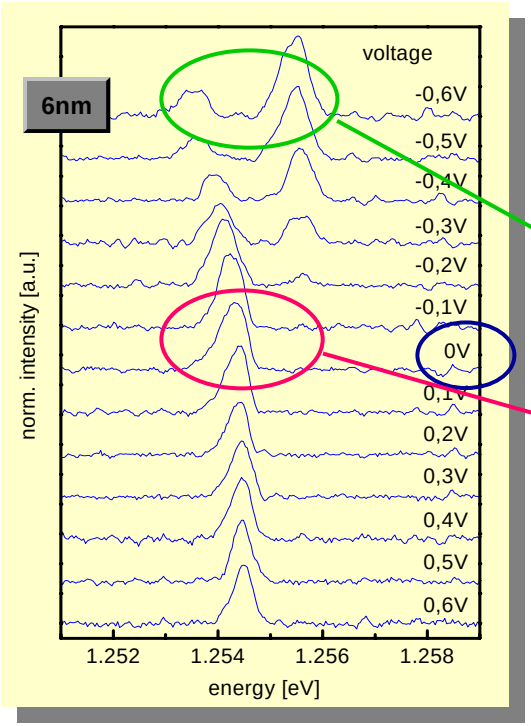
- low energy region of spectra
- leakage current at forward bias
- for reverse bias coupled state splits

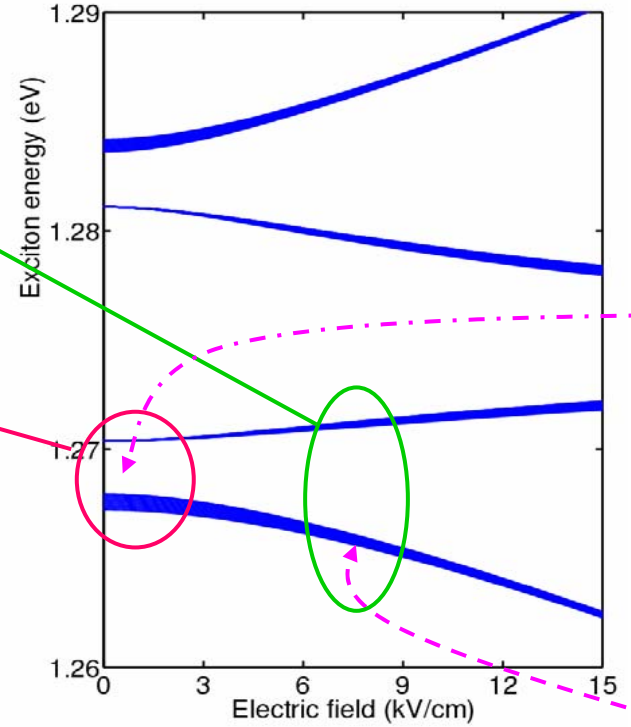
splitting vs dot separation

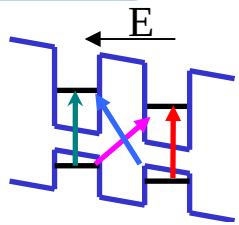


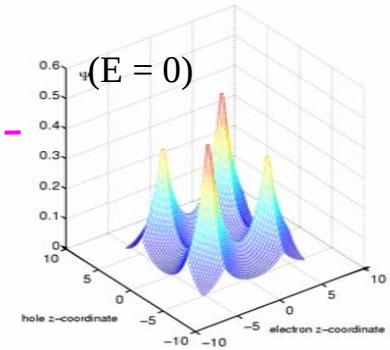
- coupling stronger for smaller separations
- larger field needed to see ‘splitting’

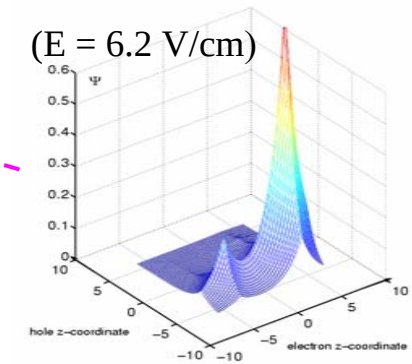
INTERPRETATION











(widths give oscillator strengths)

- low E - one mixed state optically active
- increasing E, two modes become optically active
- E-field decouples states

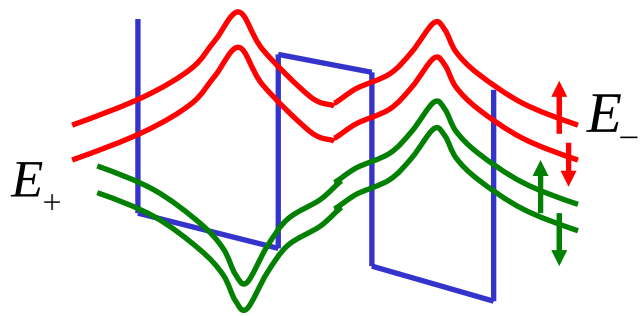
controlled QD coupling needed for gate

also, control of emission with E

2-QU BIT GATE FOR SPINS

- spins in coupled QD's
- need to set qu-bits separately in realistic, closely spaced QD's
- qu-bits from spin states of exact single particle functions, independent for large fields

one particle states

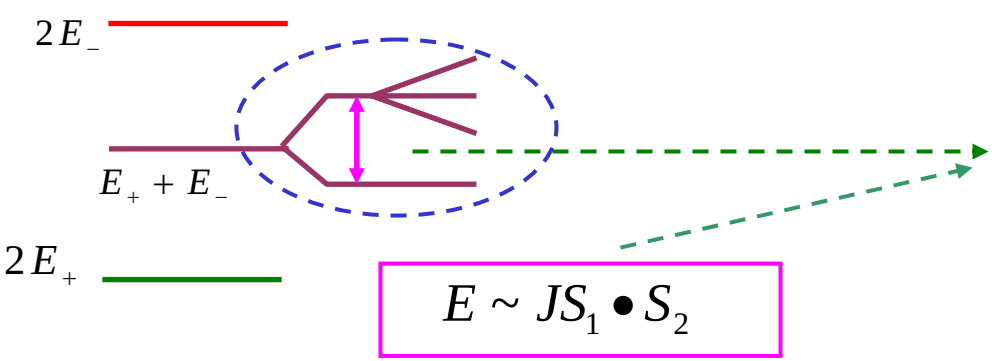


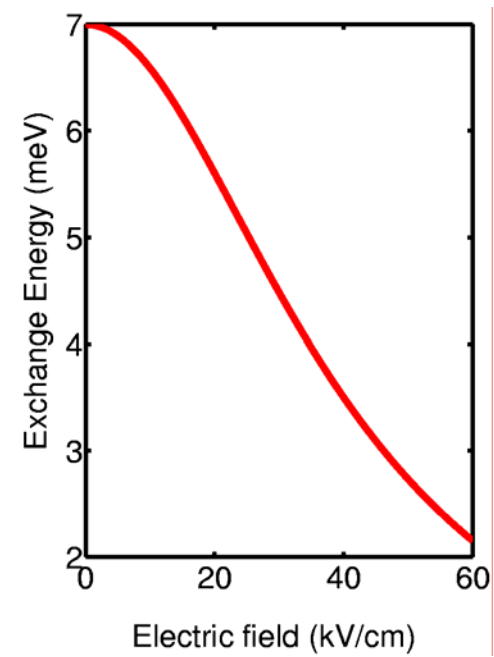
$$\phi_{a,b}(r) = \phi_l(r) \pm \phi_r(r) \left| \downarrow, \uparrow \right\rangle$$

- coupling in two particle states

e.g., $(\Psi_+(\vec{r}_1)\Psi_-(\vec{r}_2) - \Psi_-(\vec{r}_1)\Psi_+(\vec{r}_2)/\sqrt{2})$

$$x\left(\left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle + \left|\uparrow_2\right\rangle\left|\downarrow_1\right\rangle\right)/\sqrt{2}$$



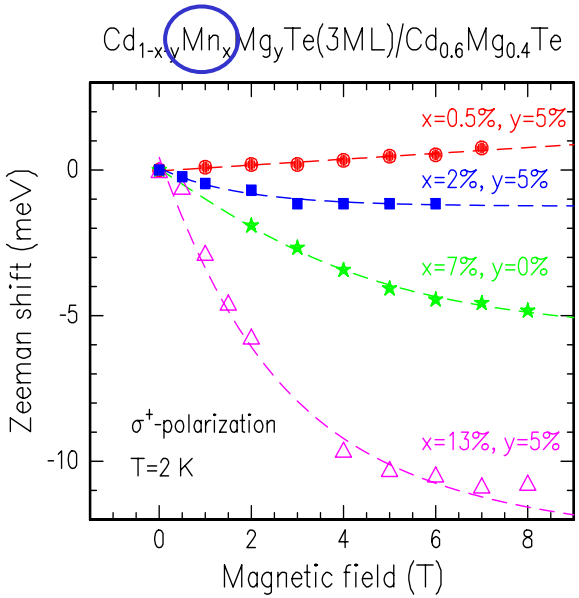


J from separation between singlet and triplet states

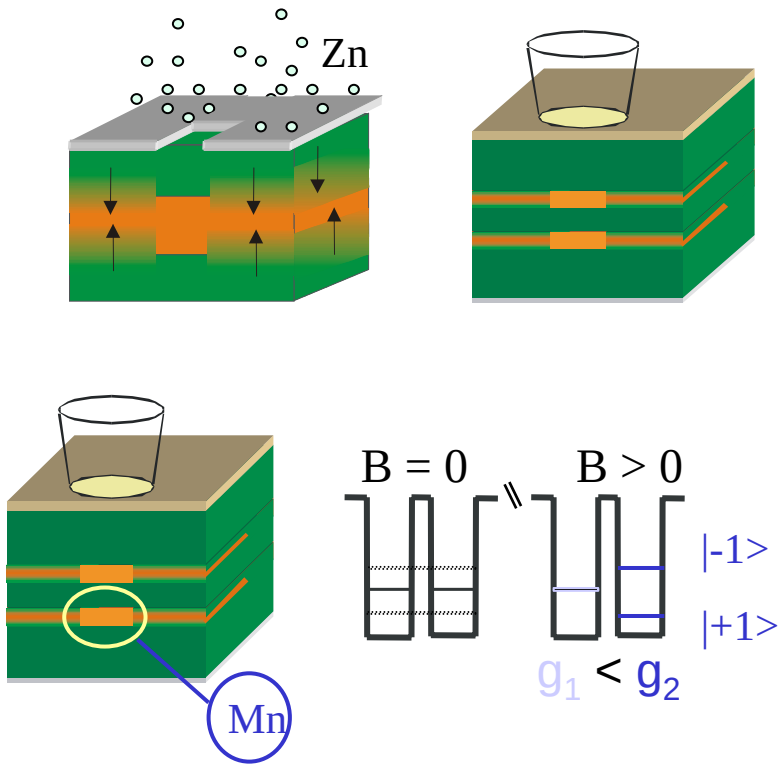
COUPLED DOTS BY SELECTIVE INTERDIFFUSION

Mn doped II-VI QD's

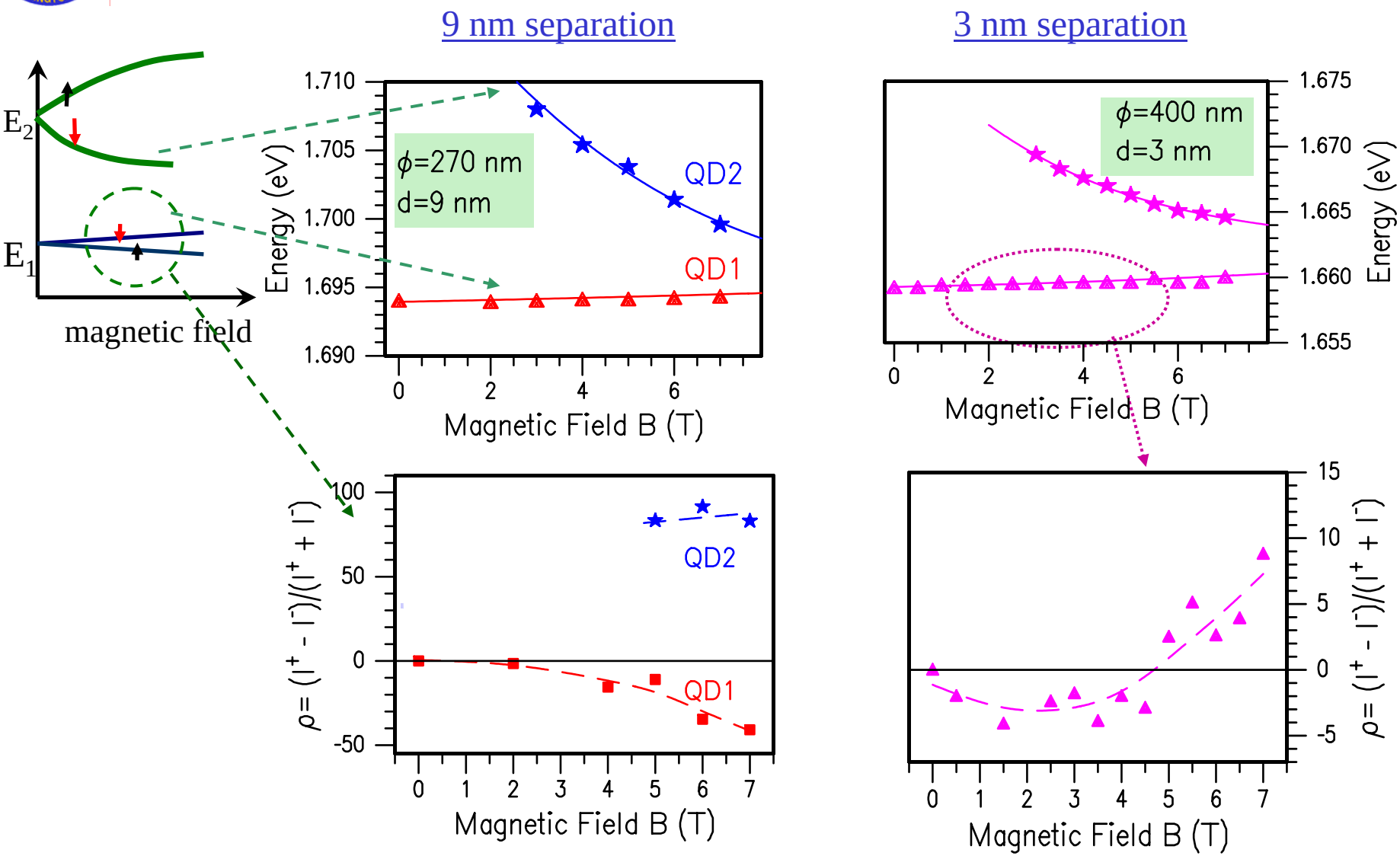
- Mn selectively incorporated
- spin splittings greatly enhanced by exchange interaction with Mn
- enhanced control of interdot coupling

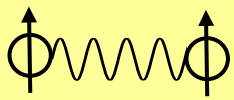


- coupled QD's formed by lithography and selective interdiffusion in II-VI's
- gives wide range of sizes and control of quantum dot separation



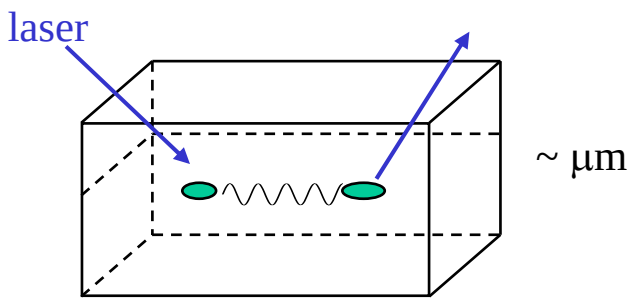
COUPLING OF II-VI QD's



- single dot qu-bits
- coupled of dots
- microcavity coupling 

CAVITY COUPLING OF DOTS

I. fast, distant, frequency selective coupling



- two mode cavity polariton
  ('strong coupling' ~ maintain coherence)

$$\left(g_{e-photon}^2 - \frac{1}{4}\left(\gamma_{elec} - \gamma_{cav}\right)^2 \right) > 0$$

$$g = \sqrt{\frac{e^2 f}{4\pi\kappa\varepsilon_0 V_m}}$$

needed:
- cavities with large Q, small V_m
- QD: large oscillator strength f

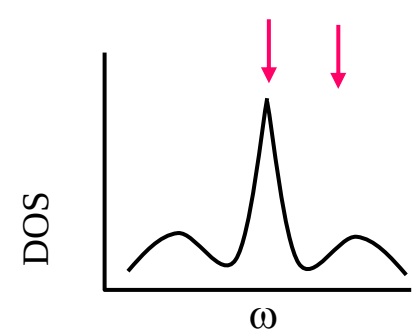
II. enhanced on-resonance emission (Purcell effect)

$$F_P = \frac{3}{4\pi^2} Q \frac{\lambda_C^3}{n^3 V_m} \qquad Q = \frac{\lambda_C}{\Delta\lambda_C}$$

need:
large Q, small V_m

suppressed off-resonance emission

need: small off resonance density of states ('leaky modes")

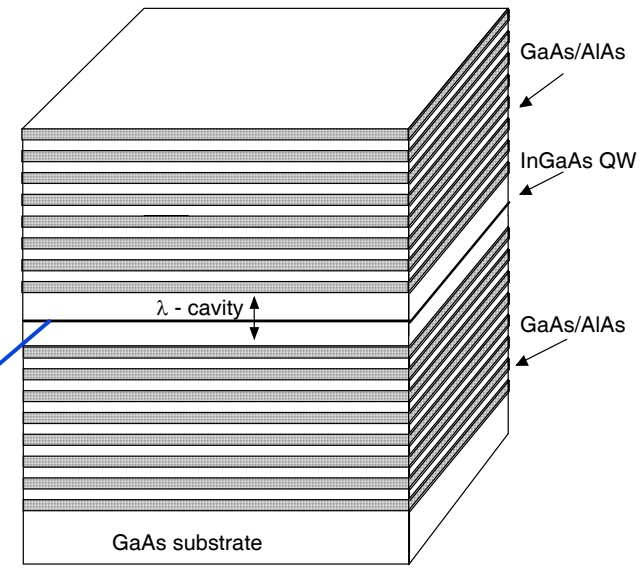


photon density of states

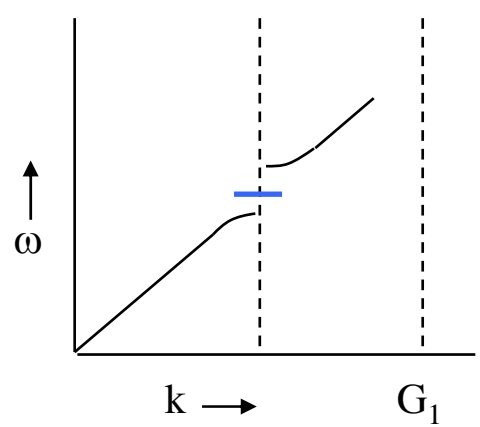
LAYERED CAVITY (VCSEL)

- λ cavity ~ 250 nm
- highly reflecting AlAs/GaAs Bragg mirrors
- 5-7 nm $In_{0.10}Ga_{0.90}As$ well as optically active material
- confined discrete 'vertical' photon mode

- VCSEL reduces photon DOS to 2D



Compare: 1D gap state

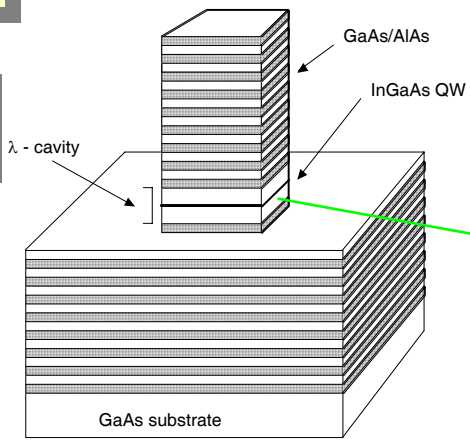


finite superlattice:
→ gap state not completely localized vertically

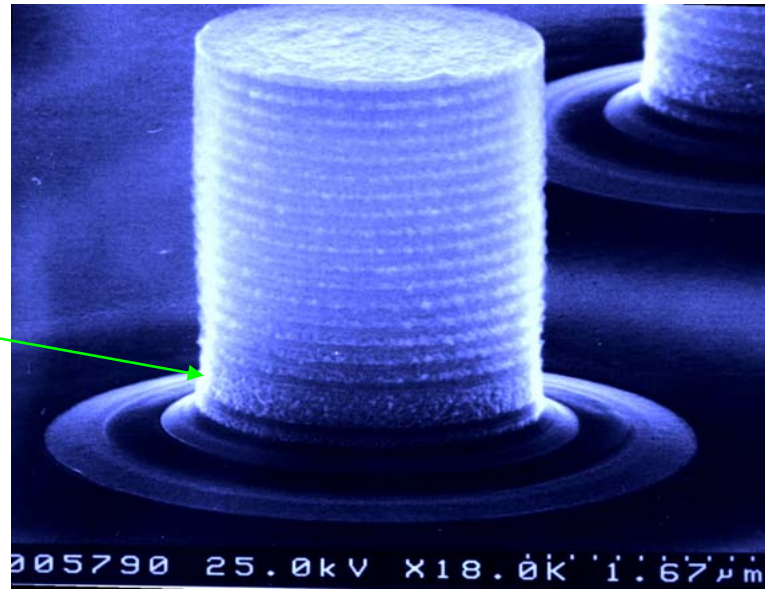
ETCHED MICROCAVITY STRUCTURES

vertical confinement:
Bragg mirrors

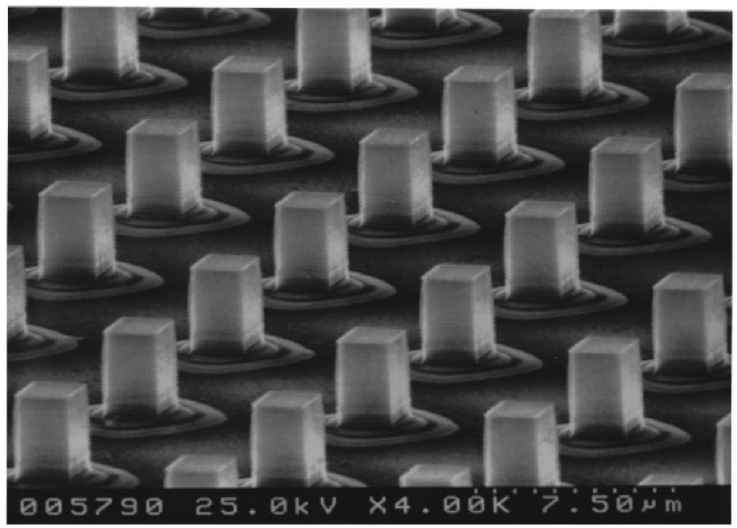
horizontal confinement:
dielectric discontinuity



SEM of cylindrical cavity



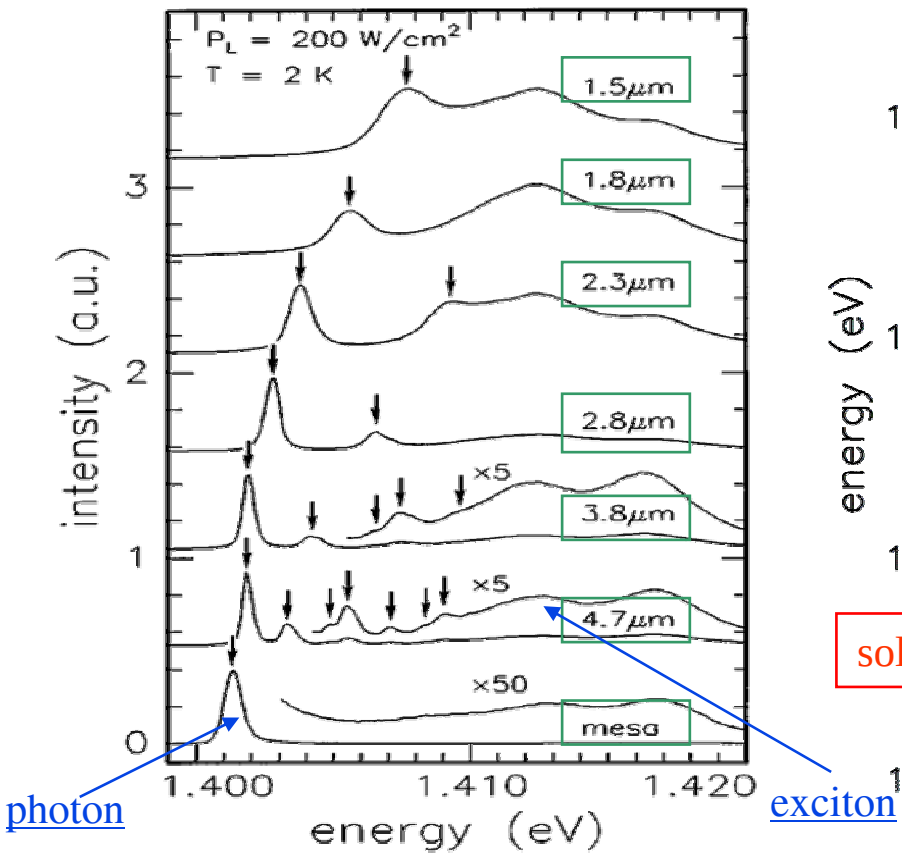
array of square cavities



- lithography (dry etching) gives lateral confinement ~ µm's
- seek to modify photon density of states, mode energies and symmetries
- seek confined, discrete photon modes
- single photon mode of interest in e.g., low threshold lasers or photon qu-bits

PHOTOLUMINESCENCE OF CAVITIES

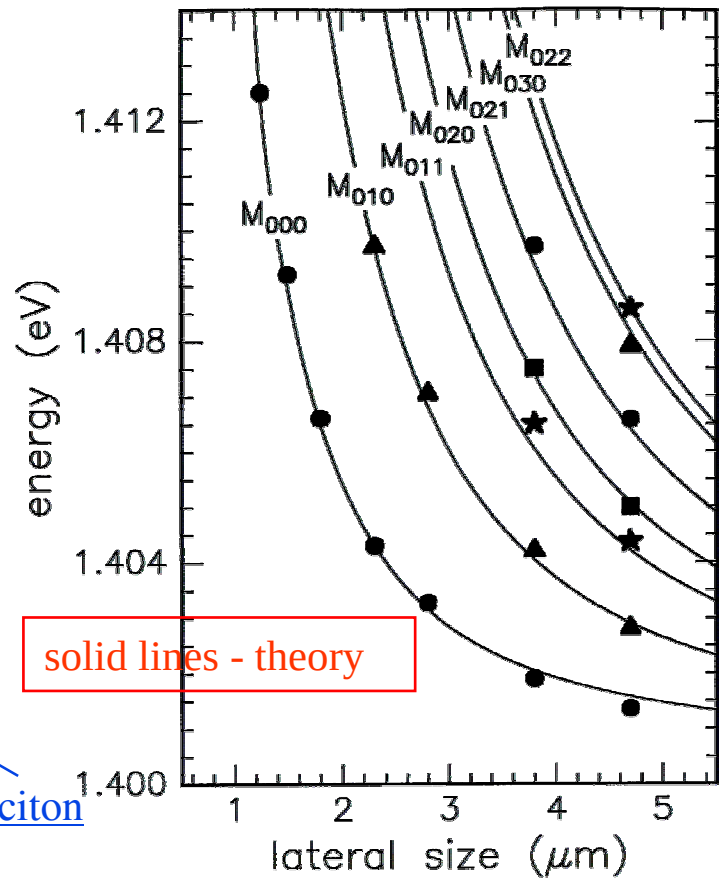
PL spectra vs. cavity size

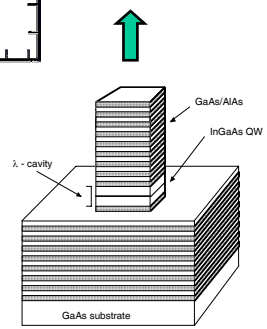


photon

exciton

'confined' photon frequencies



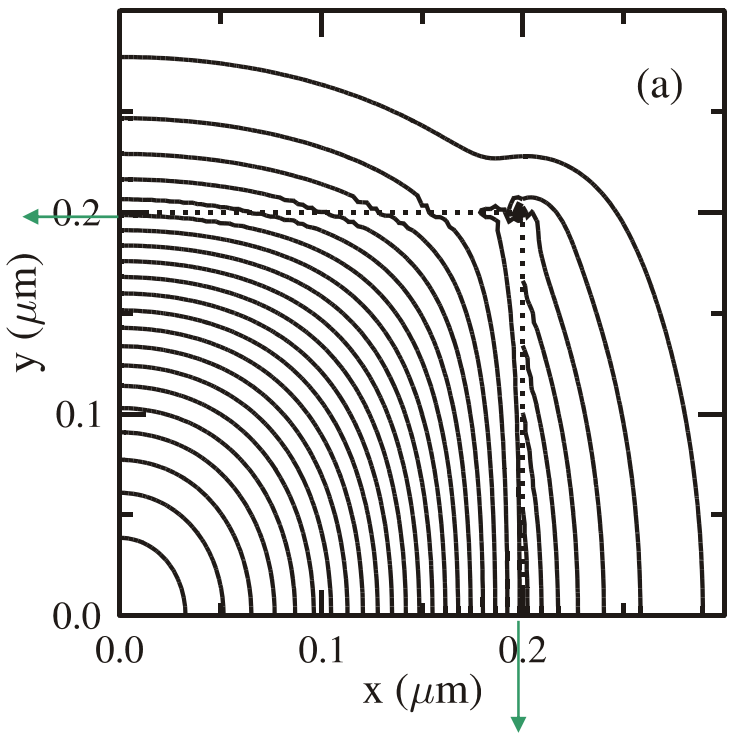


- well separated, weakly coupled exciton-photon polaritons
- photon frequencies increase with decreasing cavity size
- rich picture of cavity photons
- in quantitative agreement with calculations

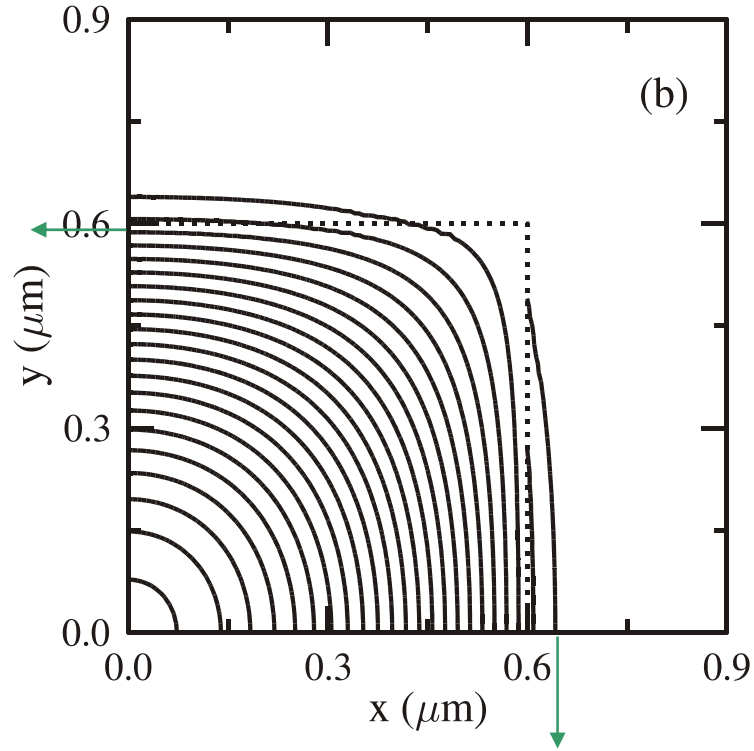
(PRL **78**, 378 (1997))

PHOTON MODES

E-field of 0.4 micron cavity



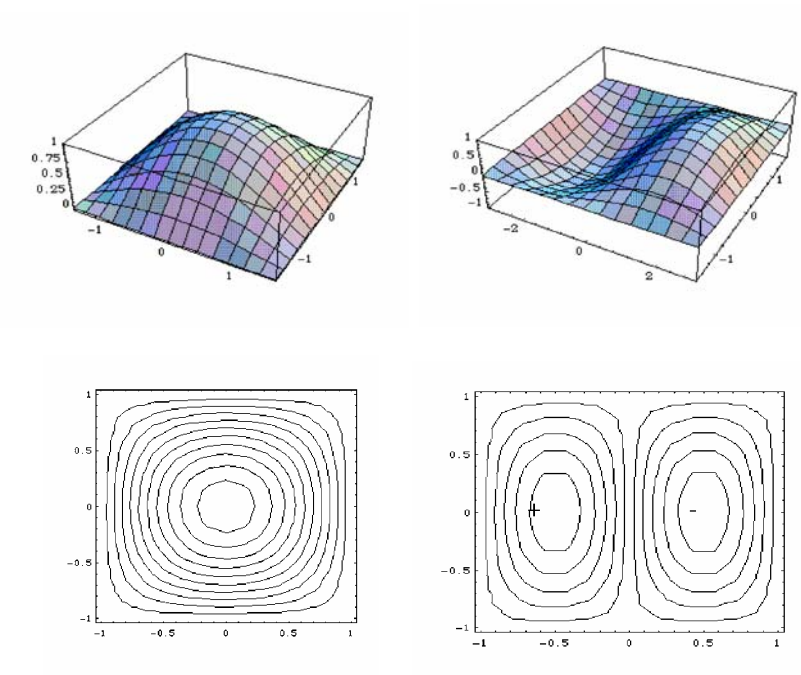
E-field of 1.2 micron cavity



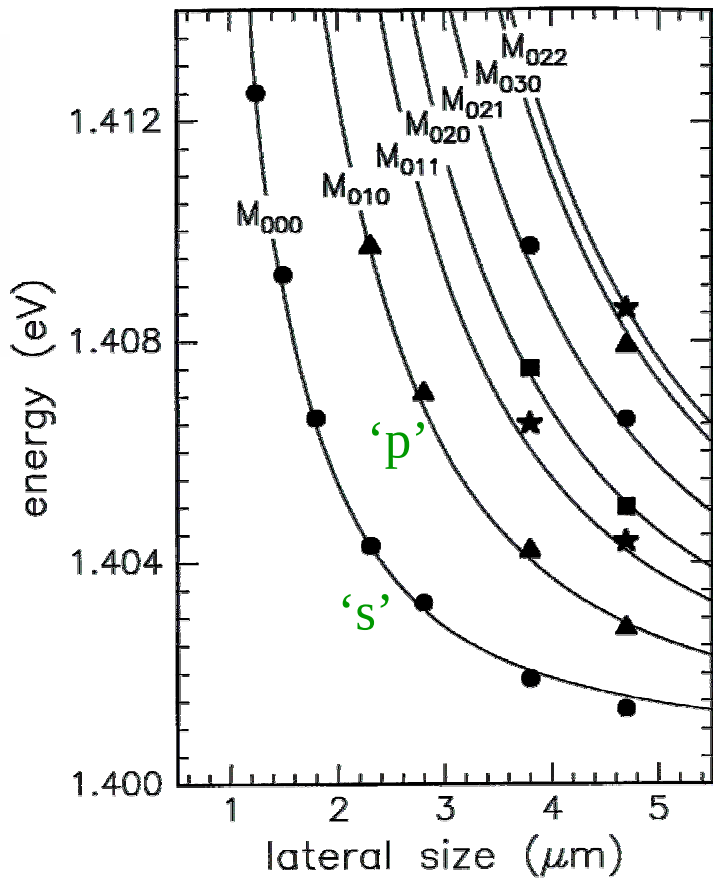
- numerical ‘boundary element’ calcn’s for non-separable horizontal motion
- more fields outside small cavities/needed to explain expt
- small asymmetry from polarization degeneracy

SINGLE CAVITY MODES

2D s-like mode 2D p-like mode



(E-fields)

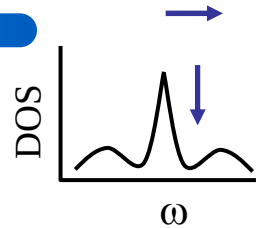


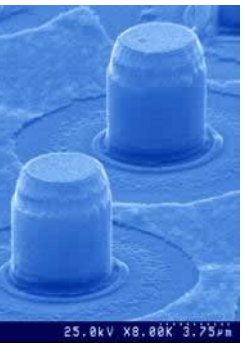
- calcn's in quantitative agreement with no fitable parameters
  (no photon many-body effects, and small relatively fabrication damage)
- picture of modes analogous to electronic states of quantum dots
- predictive power

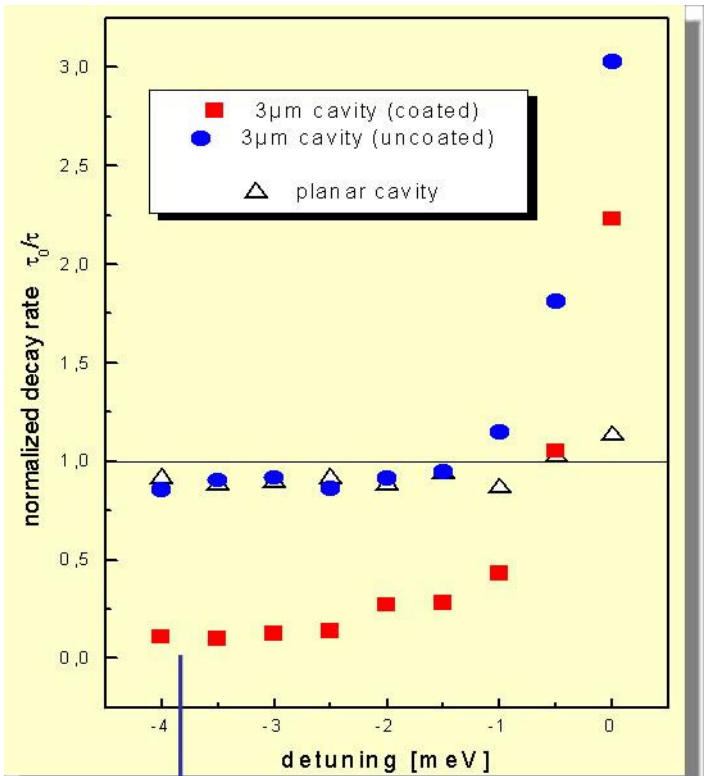
ENHANCEMENT/SUPPRESSION OF EMISSION

- InGaAs interface QD's in microcavity
- gold coated to reduce leaky modes
- on resonance emission enhanced by ~x5
- off resonance emission reduced nearly x10

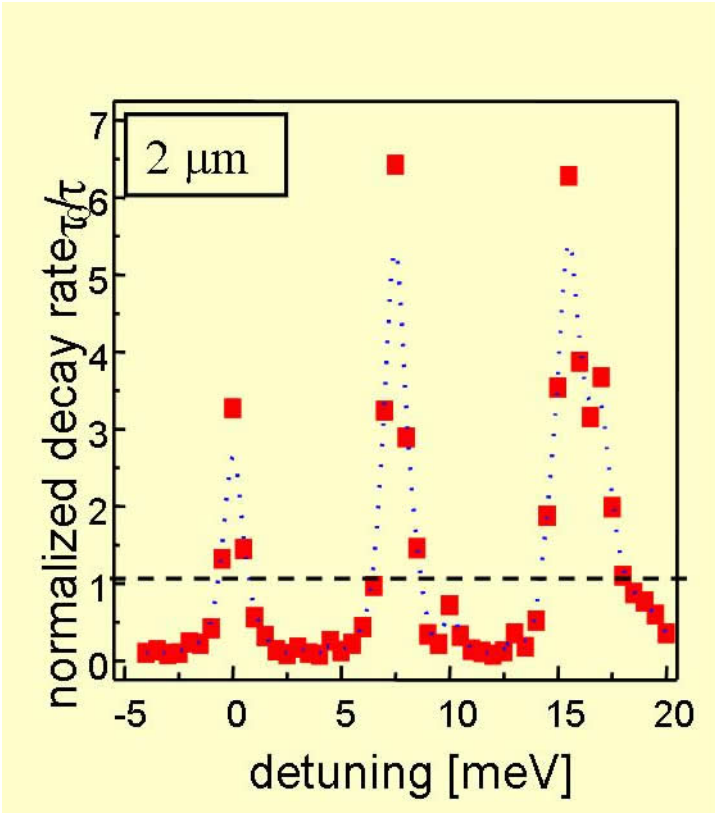
detailed control over of enhancement/suppression with detuning moving through modes







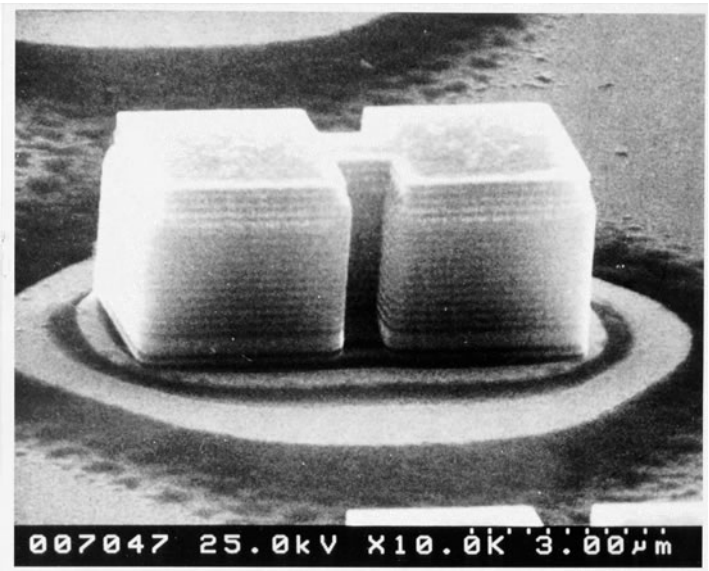
suppression greater for higher cavity Q



order of magnitude control over emission times

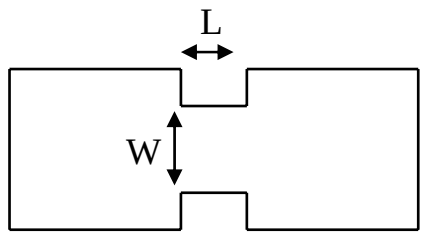
COUPLED PAIRS OF CAVITIES

structures

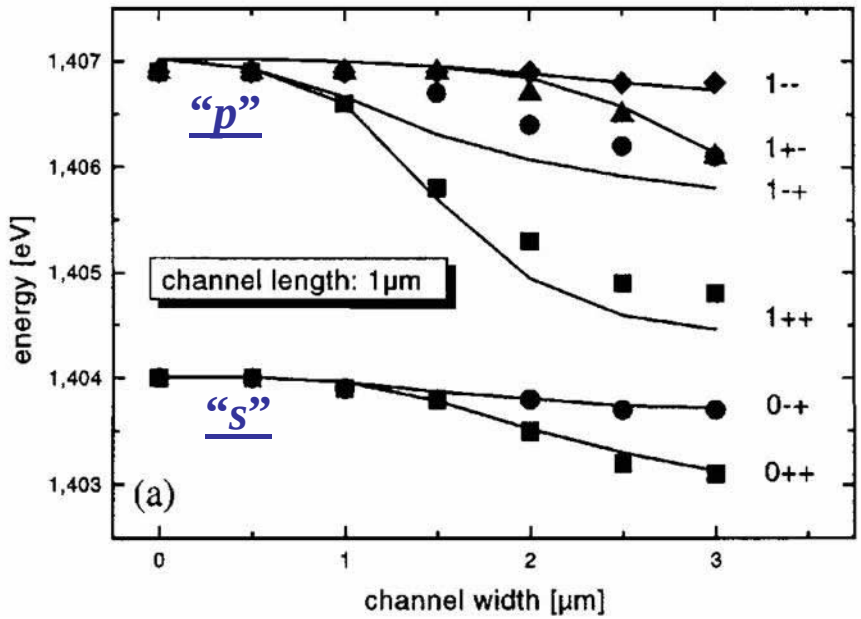


- seek to control mode symmetry, energy, volume
- single photon polarization states may be quantum information carriers

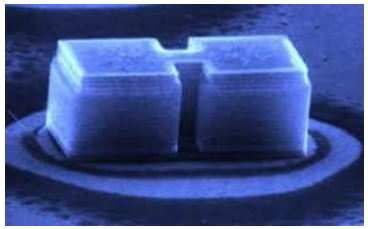
mode freq's studied as function of L, W

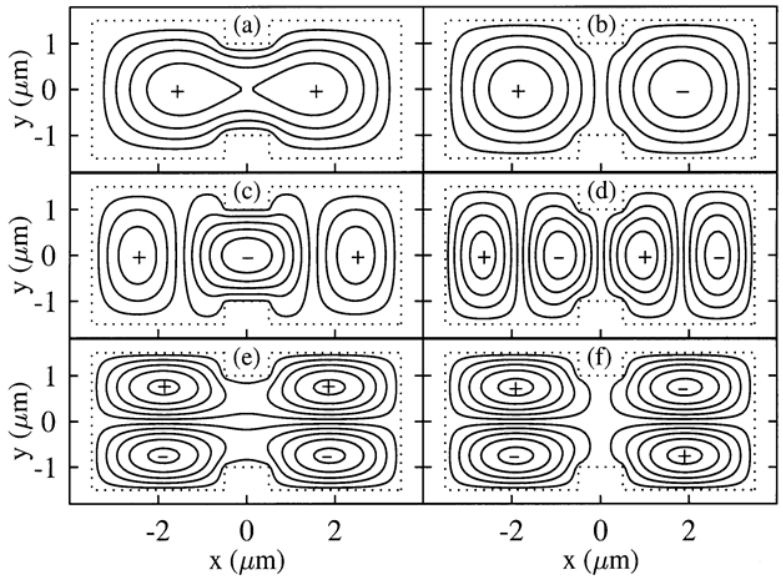


PL results – splittings



MODES OF "PHOTONIC MOLECULES"





bonding/antibonding modes

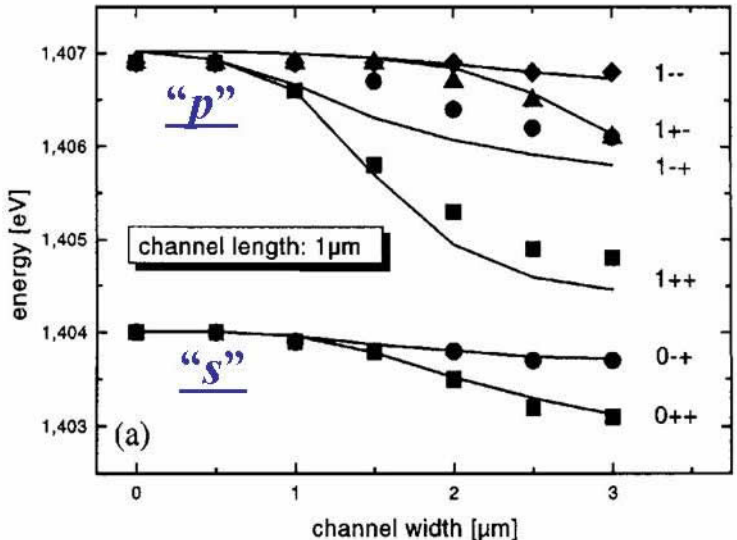
(σ–like orbitals from *s* modes)

(σ–like orbitals from p_x modes)

(π–like orbitals from p_y modes)

- coupled cavities have rich pattern of modes
- splittings controlled by cavity couplings

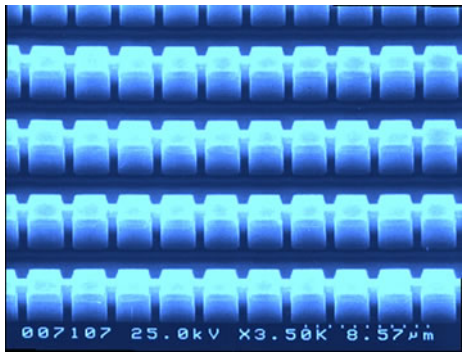
account quantitatively for L, W dependences



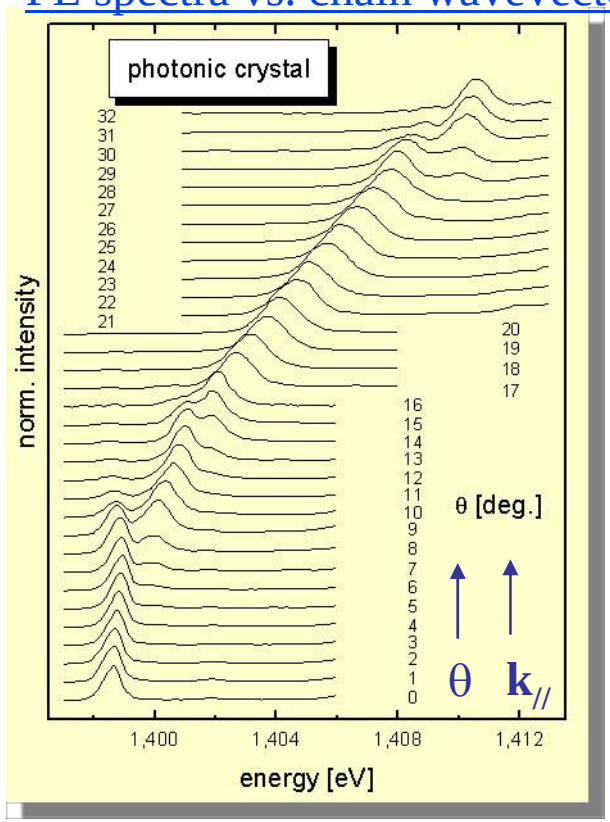
(PRL **81**, 2582 (1998))

BAND GAPS IN CHAINS

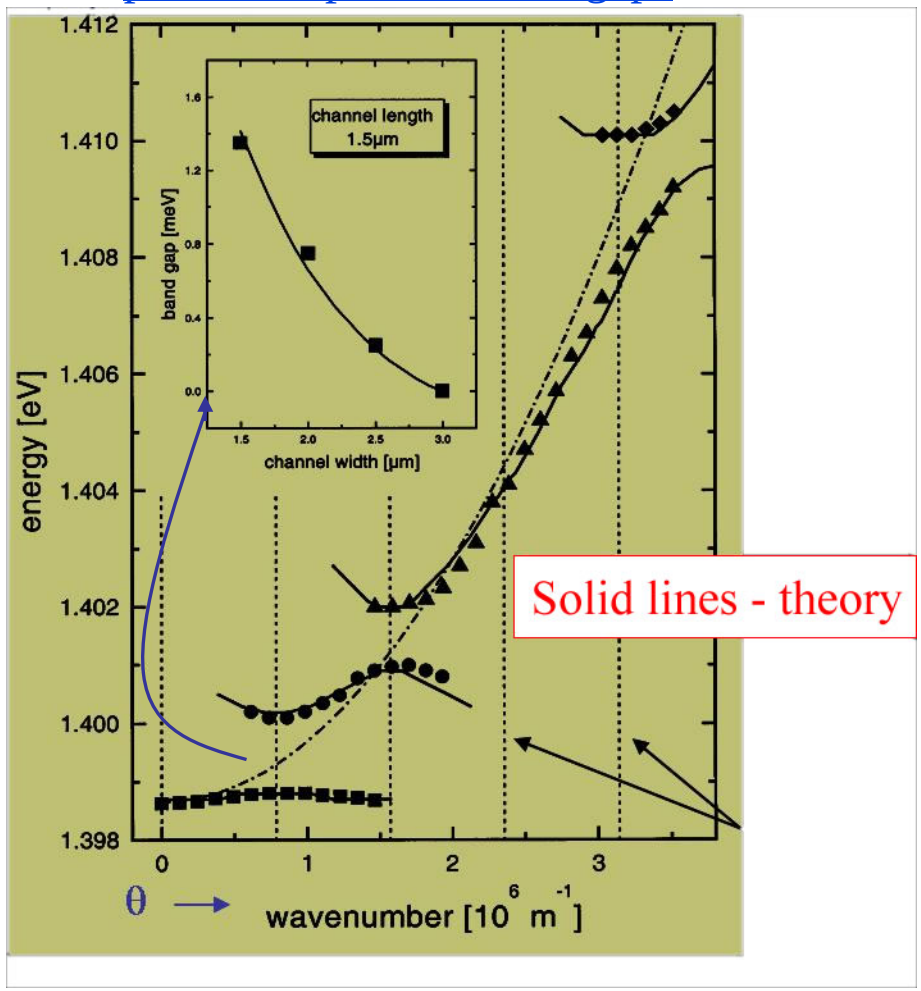
chains of cavities



PL spectra vs. chain wavevector



photon dispersion/band gaps

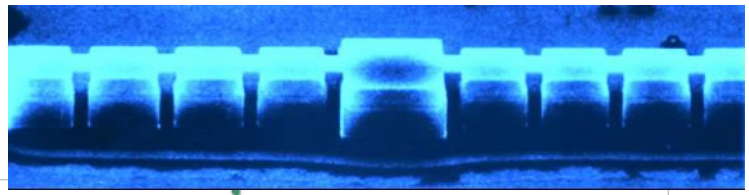


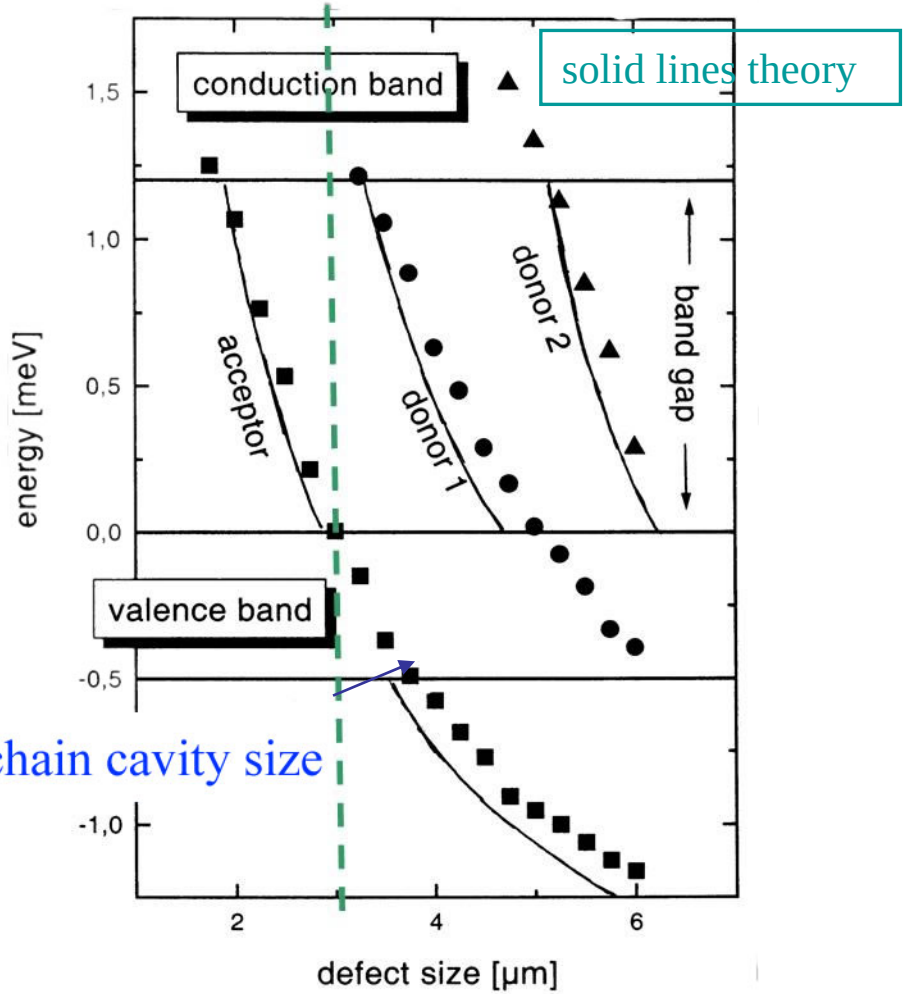
- band gaps out to 4th Brillouin zone
- theory is BEM for vector Maxwell eqns
- 3rd gap is ~ 0.035 meV

(PRL **83**, 5374 (1999))

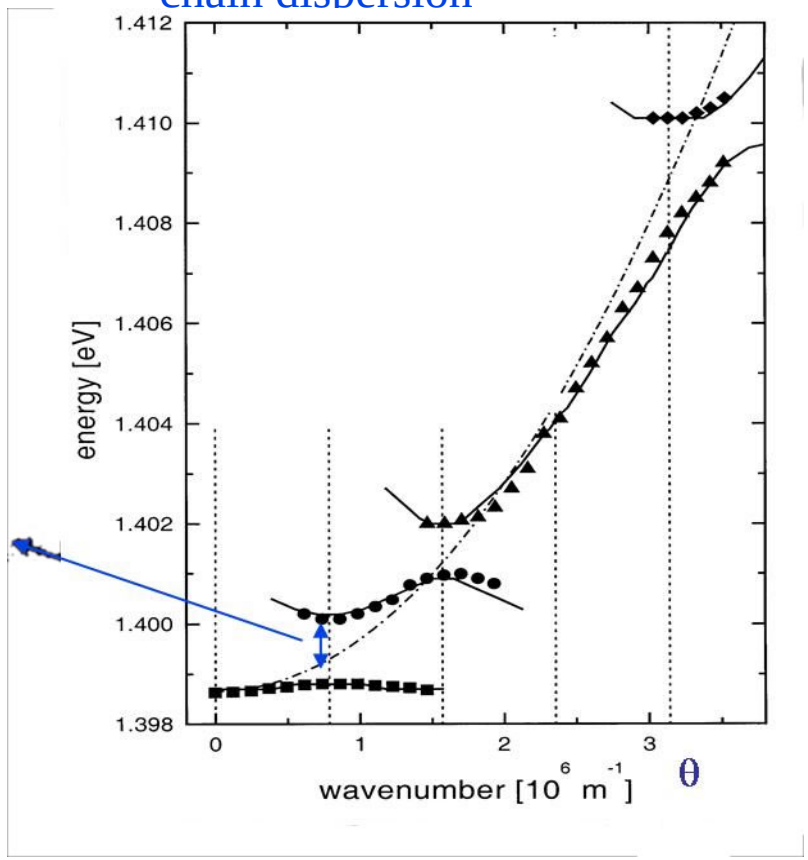
PHOTON BAND GAP STATES IN CHAINS

defect cavity states



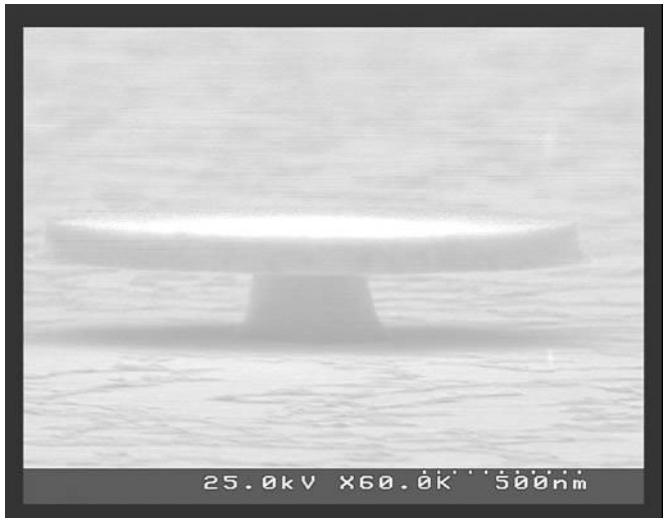


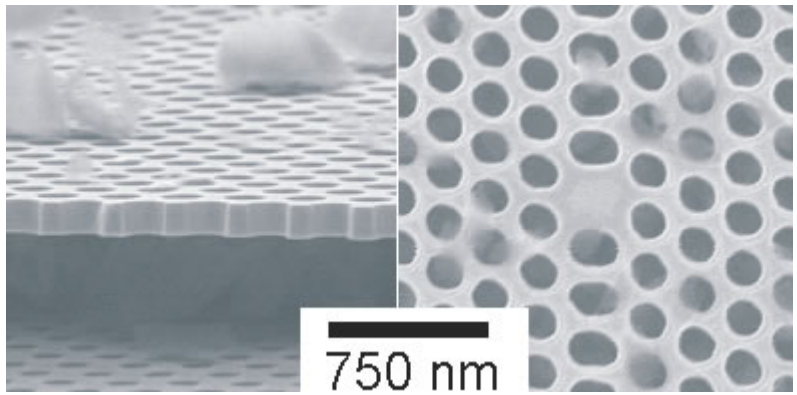
chain dispersion



- no other states at energy of gap states
- gap states potentially sharp/long lived
- of interest in lasers, LED's, waveguides
- theory in good agreement with exp't

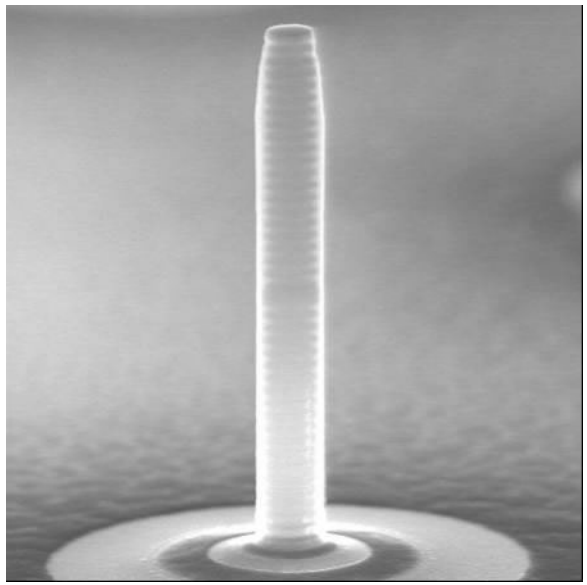
OTHER STRUCTURES

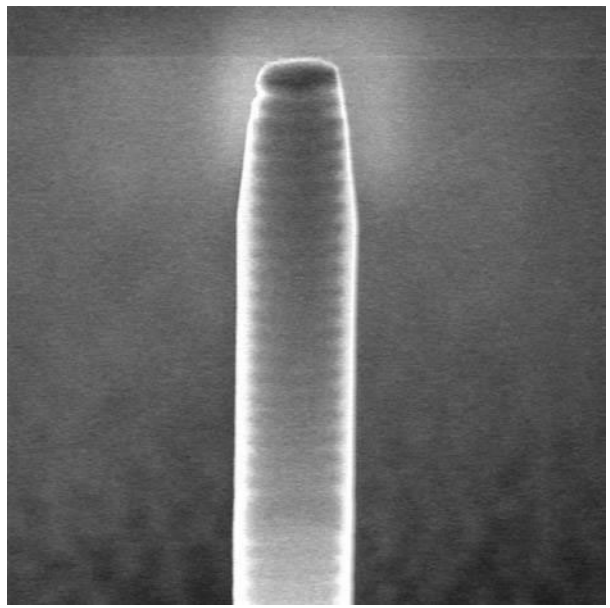




HIGH Q CAVITIES WITH SELF ASSEMBED QD's

A number of slides describing our recent work on very small, high Q cavities were described in the talk but have been deleted until this work is written up





SUMMARY

quantum dots for qu-bits
- exciton
- spin qu-bits

direct coupling of QD qu-bits
- coherent coupling
- coupling controlled by E –field

microcavities
- control emission
- search for high Q cavities for strong coupling