Intersubband Transitions: Their Physics and Their future.

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ITQW Ambleside Sept 2007.

Outline

*What are ISBT's?

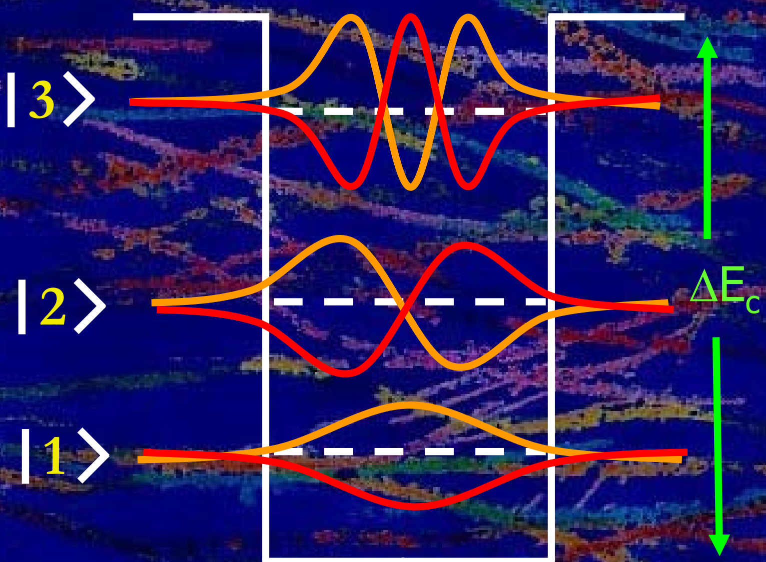
*What's good (and bad) about them?

BIG JUMP!

*New wrinkles to try for improved devices.

*New bits of science to try, just for the sake of it.

Confinement Energies



$$E_{12} \approx 3h^2 / m^* d^2$$

* d~ few nm

*ΔE_c ~ few 100 meV.

*Much wider range of material possibilities than interband-based devices.

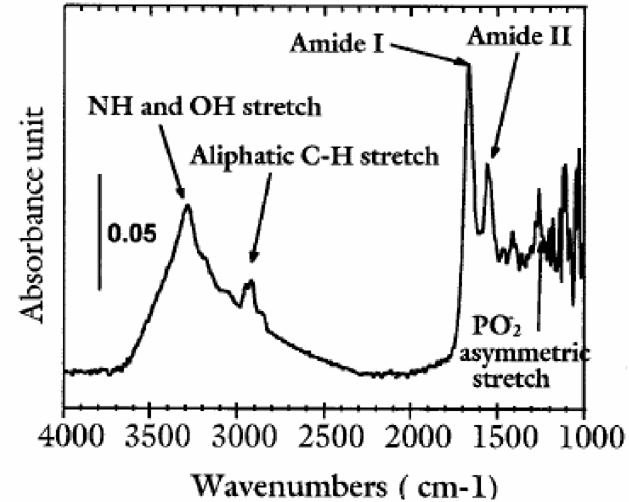
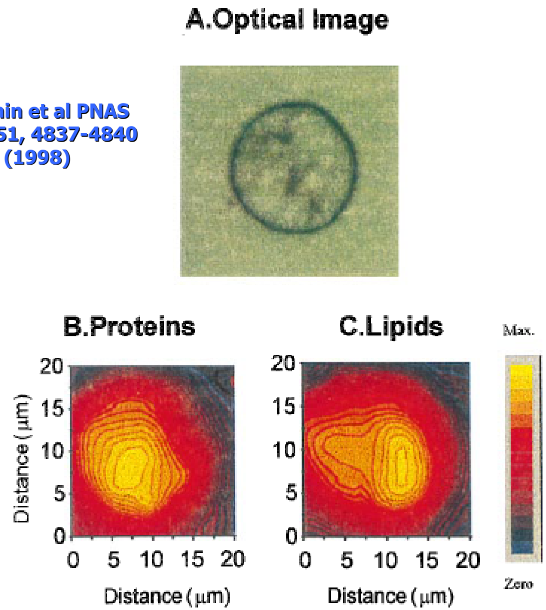
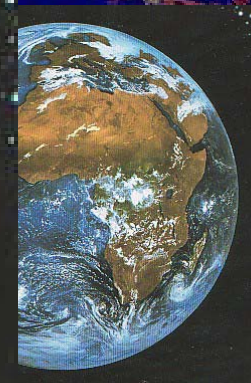


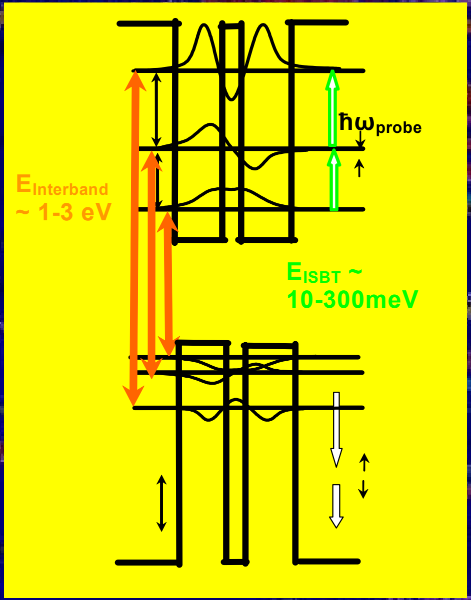
FIG. 1. Infrared spectrum of a mouse UN2 hybridoma B living cell, recorded with an aperture of 3×3 μm^2. The instrumental resolution was set at 4 cm^{-1}, and the spectrum displayed is the result of 128 co-added scans (the total recording time is 55 sec).

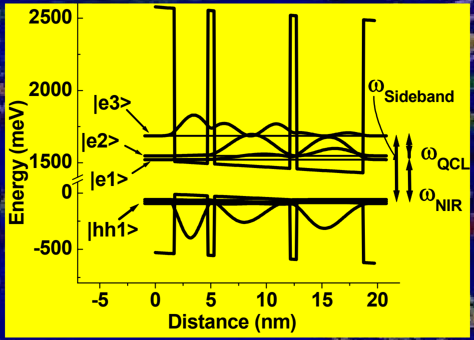
N Jamin et al PNAS USA 951, 4837-4840 (1998)





Transition strengths





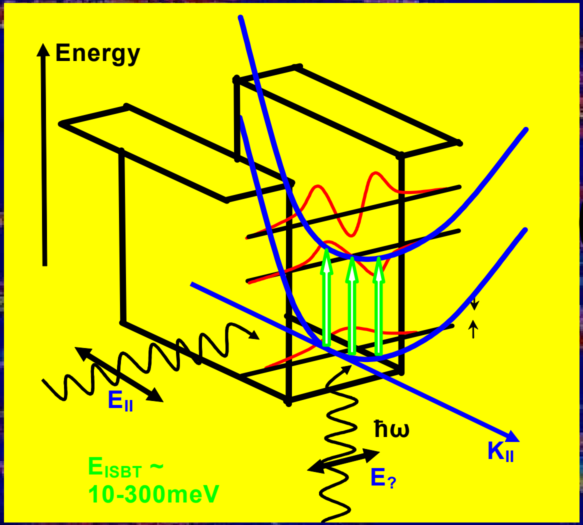
*Δn-odd selection rule (in principle).

* z_{12} ~2-3 nm. i.e. big!

* Highly anisotropic absorption (dichroism) and dispersion (birefringence).

* Optical response has unusual quasi-cylindrical point group symmetry.

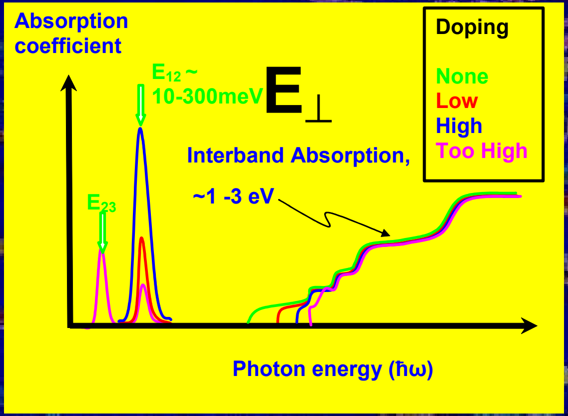
Tunable ISBT oscillator strengths.

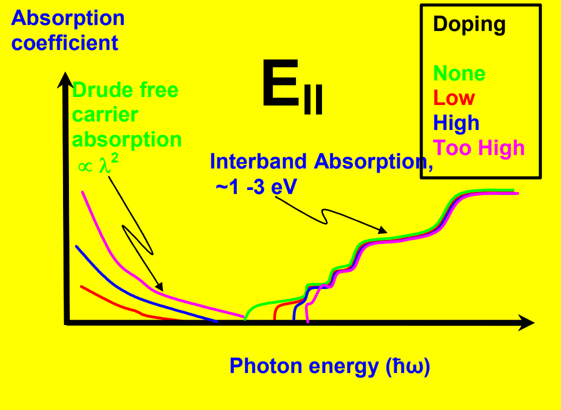


*ISBT transition energy (almost) independent of $k_{||}$

* ISBT absorption is peaked

* Absorption ∝ electron density





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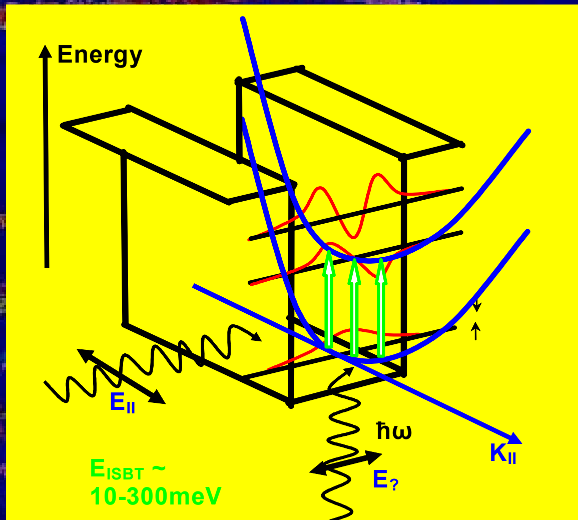
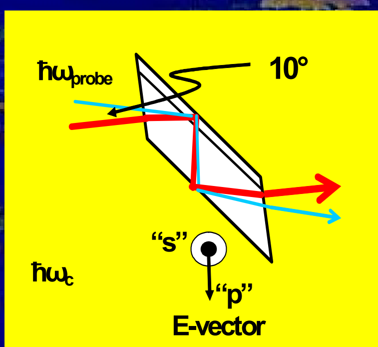
Dipole selection rules.



*ISBT oscillator is <u>z-polarised</u>

* Normally no absorption at normal incidence.

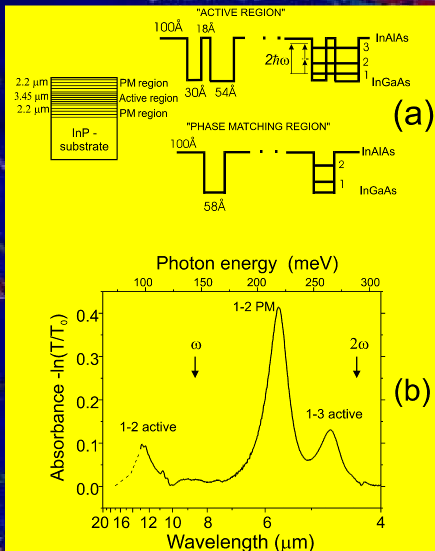
* No vertical laser cavities



* Can be dodged with e.g VB and non-Γ CB material. In principle.

* Makes for easy absorption spectroscopy though!

Designable dispersion.

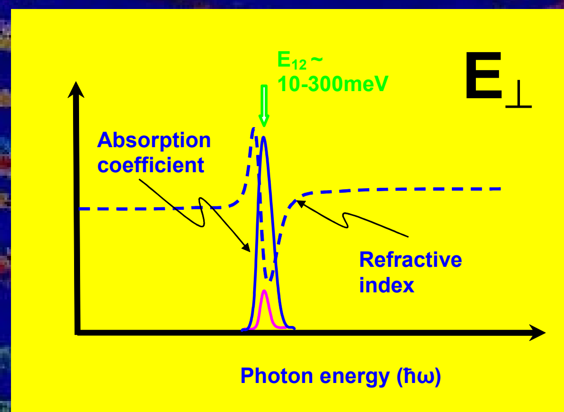


*ISBT peak is surrounded by transparent regions.

* Can add oscillators to waveguide to design-in desired dispersion characteristics.

* Useful for coherent optical experiments.

* Electro-optical control possible through QCSE.



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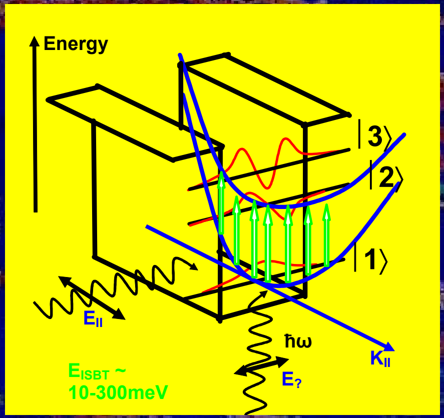
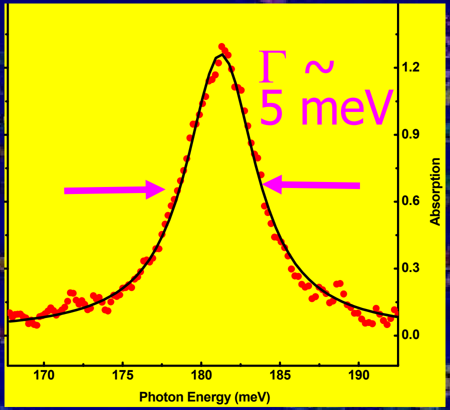
Broadening mechanisms (1).

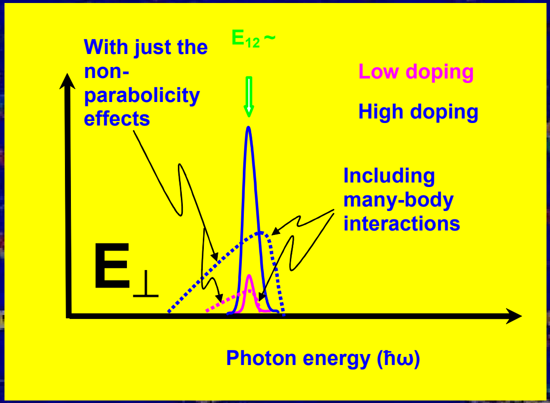


m increases with energy (non-parabolicity), broadens transition.

* Exchange correlation effects counteract this broadening effect.

* Often a good fit to Lorentzian lineshape.





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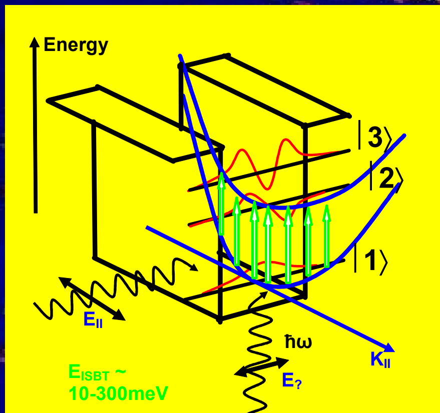
Broadening mechanisms (2).

*300k Linewidth ~10 meV , <<kT!

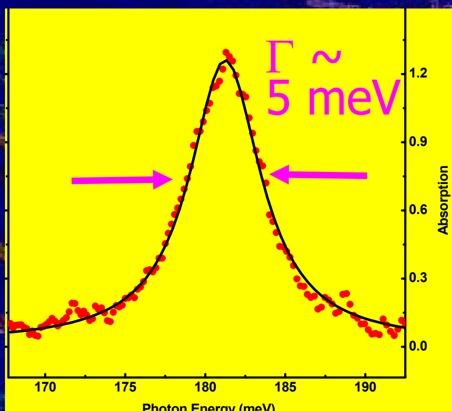


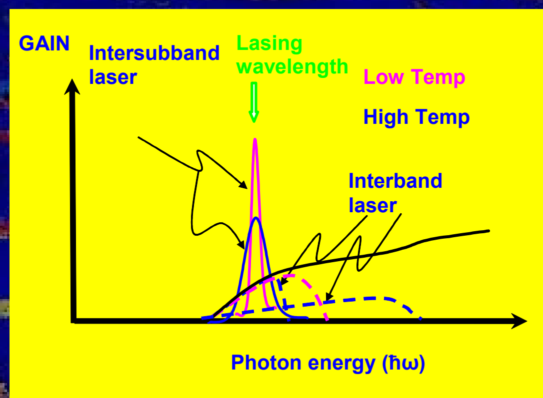
* Interface roughness and phonon scattering W~ $1/q^2$

* Low-q acoustic Phonons do the damage it seems.

* Scattering respects dipole selection rules.

* Temperature insensitivity VERY good for laser J_0's





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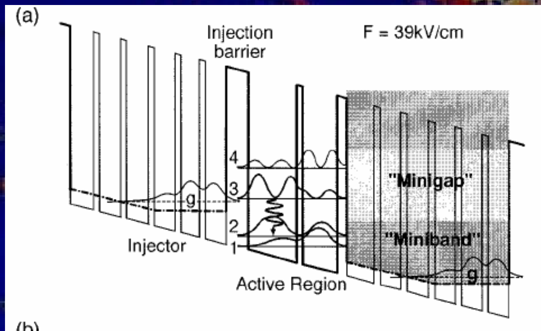
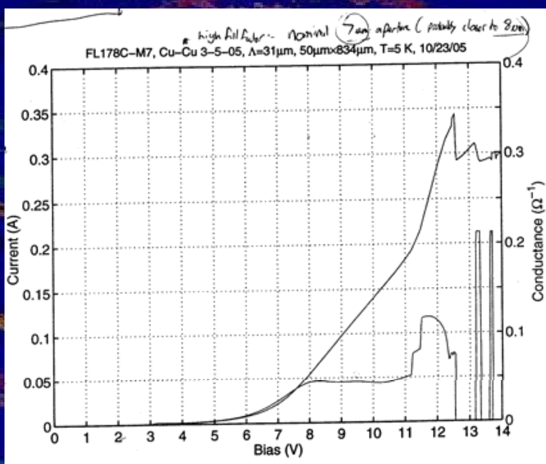
Cascaded Electron Transport Idea .



C Sirtori et al. APL 69 (19) , 2810 (1996).



* Majority carriers, insensitive to Temp and Materials quality.

* Very versatile cf pn junctions.

* Resonant tunnelling can help keep everything aligned.

* Suited to wide cavities needed for IR.

* Important "transformer" side effect.

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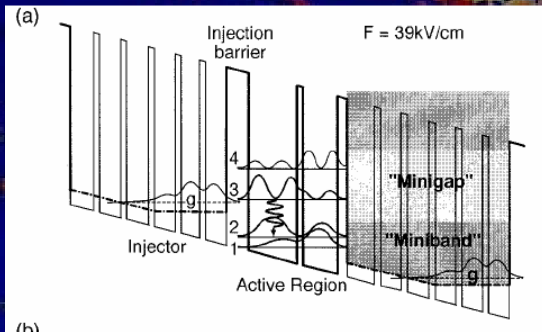
Thermal Transport .

* It's rubbish. Frankly.

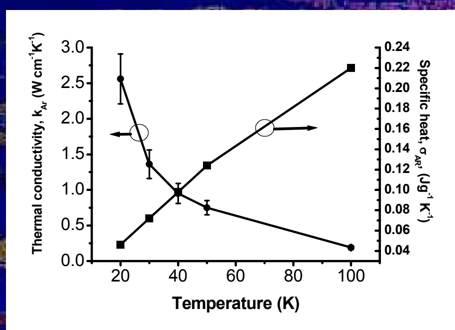


C Sirtori et al. APL 69 (19) , 2810 (1996).

* GaAs Phonon mfp's 1000 nm (50K) to ~40nm (375K)

* Heterostructures scatter phonons on nm length scales

* QCL conductivities ~ 10 x worse than bulk

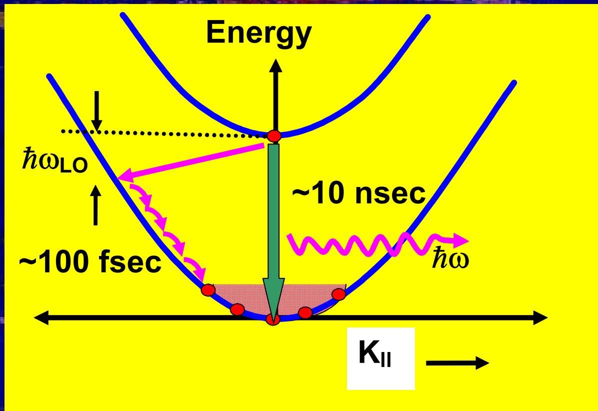


A J Borak et al. APL 82 (23) , 4020 (2003).

* Comparatively few systematic studies.

* CRITICAL for 300K CW devices.

Intersubband dynamics .



* GaAs LO phonon scattering in ~100fsec.

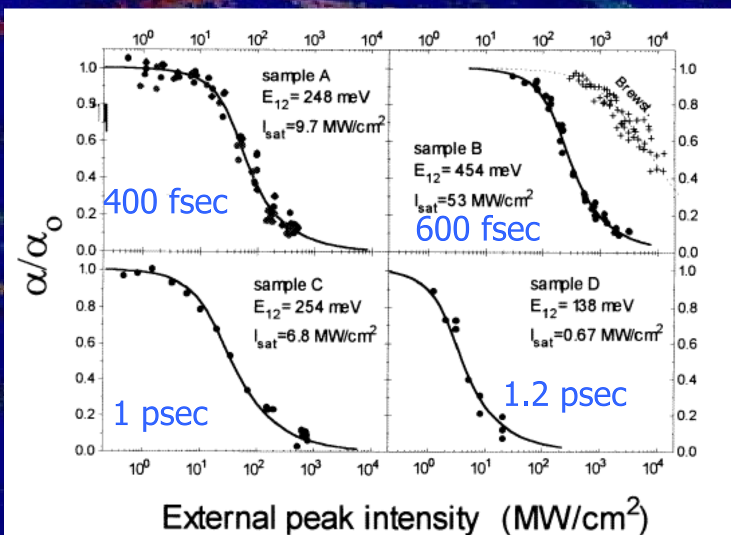
* Faster than a very fast thing.

* Poor spontaneous radiative efficiency.

* High J_{th} in lasers

* High saturation intensities in switches.

* "Phonon bottleneck" failed to appear.



K L Vodopyanov et al. Semicond. Sci. Tech !2 , 08 (1994).

Half time summary .

* Intersubband transitions are.....

Tunable in energy and strength throughout IR and FIR

Fast, (due to intrinsic non-radiative recombination channel)

Quite sharply peaked ($\Delta\lambda/\lambda$ ~ 10% @ 300K).

Insensitive to temperature and materials.

Tunable in energy and strength throughout IR and FIR.

Fast, (due to intrinsic non-radiative recombination channel)

Quite sharply peaked ($\Delta\lambda/\lambda$ ~ 10% @ 300K).

Insensitive to temperature and materials.

What next then?

* New Materials possibilities.

* Plasmonics

* Non-linear optics for new wavelengths.

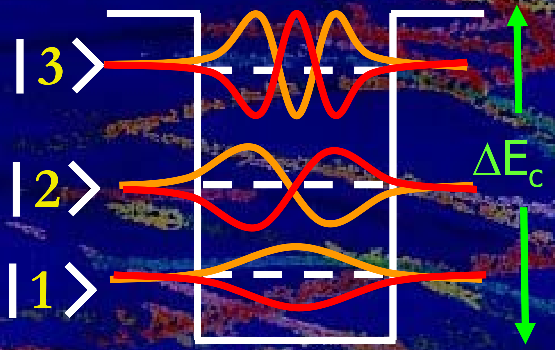
* Strongly coupled light-matter systems.

* Coherent Quantum Optical effects.

* Phonon Engineering.

* Subbands for Science:-Artificial Atoms.

New Materials.



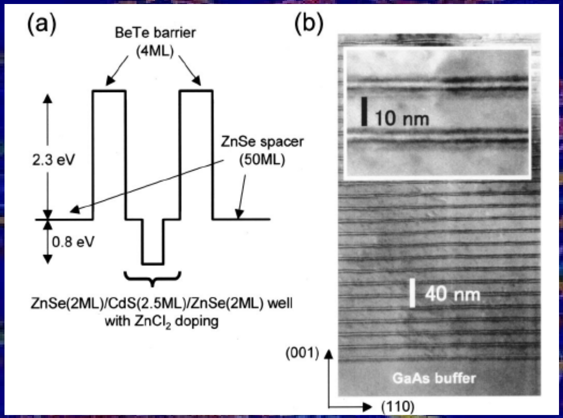
* Shorter λ's need larger ΔE_c materials

* Larger ΔE_c goes with larger bandgap and m*, and higher bond strengths.

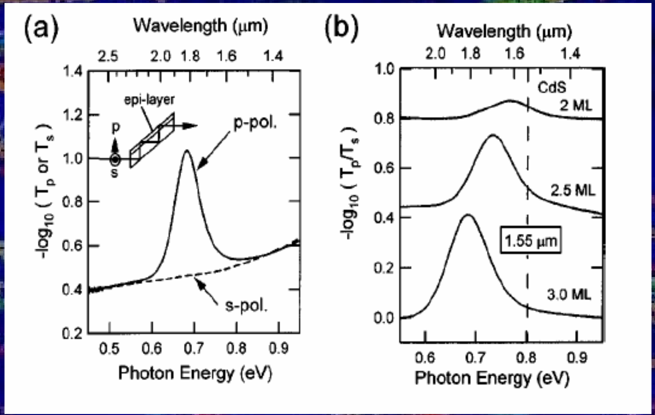
* This means higher temp growth and doping problems.

$$E_{12} \approx 3h^2 / m^* d^2$$

* Feeling Brave?



R Akimoto et al. APL 81(16), 2998 (2002). [Tsukuba]



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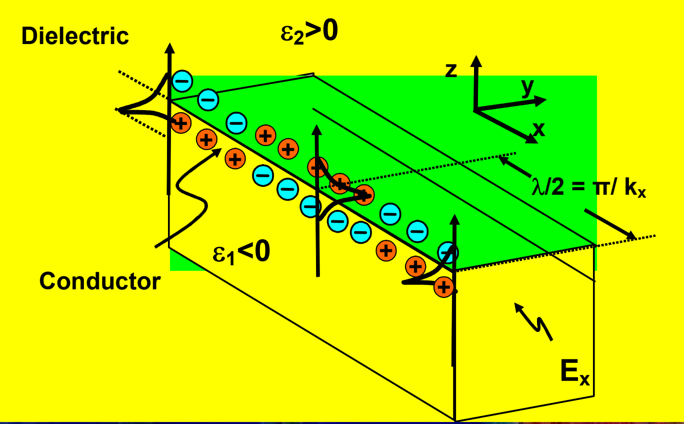
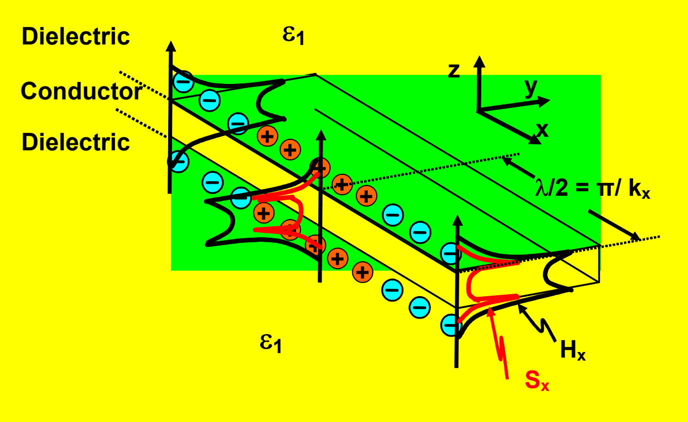
$$\omega_p^2 \approx \frac{ne^2}{m^* \varepsilon_0 \varepsilon_r}$$

Plasmonics

- *ε< 0 for ω<ω_p
- *Field Concentration- sensors
- *Shrinking Opto-Electronics
- * Metallic Optics
- * Opportunities for semiconductors!





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Plasmonics

$$\omega_p^2 \approx ne^2 / m^* \varepsilon_0 \varepsilon_r$$

*Already being used for QCL cavities.

*Compresses mode volumes.

•Way of guiding FIR in sensors?

* Quantum anisotropy means new opportunities for semiconductors!

* Negative refraction exotica possible.

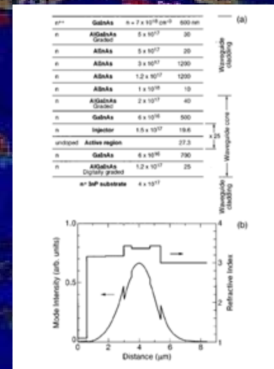
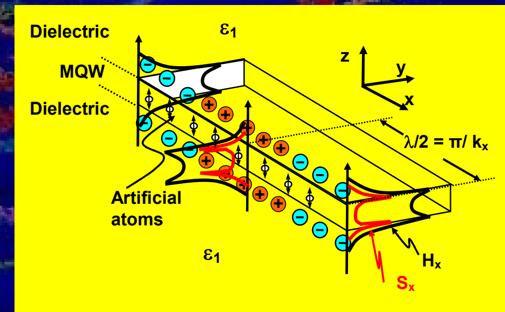


FIG. 2. (a) Schematic cross section of the quantum cascade laser structure. (b) Refractive index profile of the waveguide structure. The calculated profile of the fundamental mode of the waveguide is also shown.

Sirtori et al. APL 66 (24), 3242 (1995).



Jonathan Plumridge and CCP.Phys.Rev. B 76, 075326 (Aug 2007) .

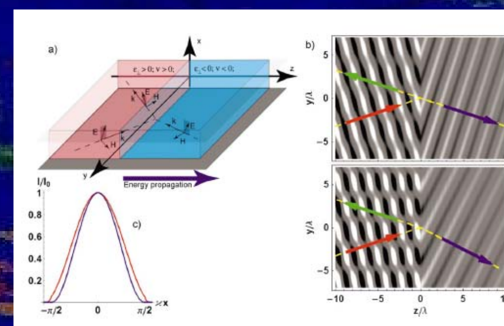


FIG. 2. (Color) Reflection and refraction at the boundary between right- (RHM) and left-handed media (LHM). (a) Schematic illustration of refraction of a TM wave at the RHM- LHM interface (ordinary wave not shown). (b) (top) The results of the exact nu-

V A Podolskiy and EE Narimanov , PRB 71, 201101,(2005) .

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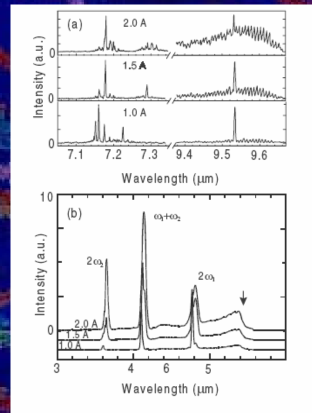
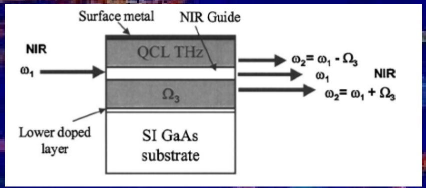
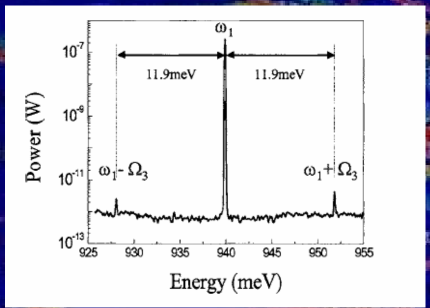
Non-linear optics for new wavelengths







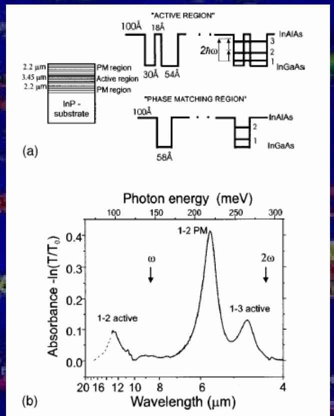
***QCL cavities have high radiation density and the intrinsic $\chi(2)$ of III-V's.**

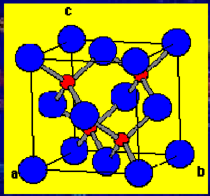
***Artificial resonances can be designed-in.**

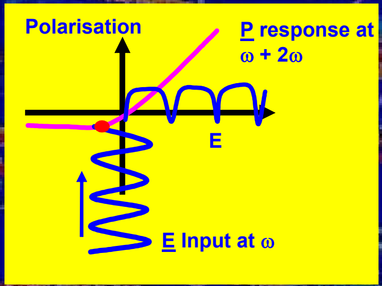
***Designable dispersion for phase matching.**

N Owschinikow et al. PRL, 90 (4), 043902-1 (2003).

S S Dhillon et al. APL 87, 071101 (2005).







K L Vodopyanov et al. APL 72(21), 2654 (1998).

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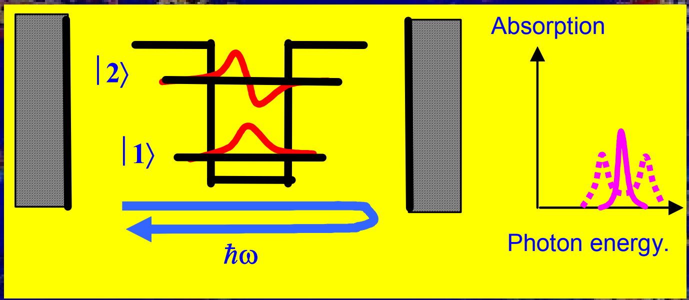
Strongly coupled cavities



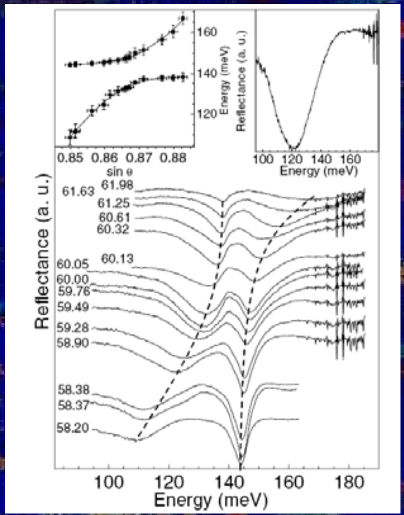
*Einstein's rules assume matter and light only perturbatively coupled.

*Small mode volume, high Q, coupling energy dominates all other terms.

*Good for weakly absorbing detectors.

*Non-Einsteinian lasers?

ET Jeynes and FW Cummings Proc, IEEE , 51, (1), 89-109 (1963).



*QCL's uniquely suitable for this.

D Dini et al. PRL, 90, 116401 (2003)

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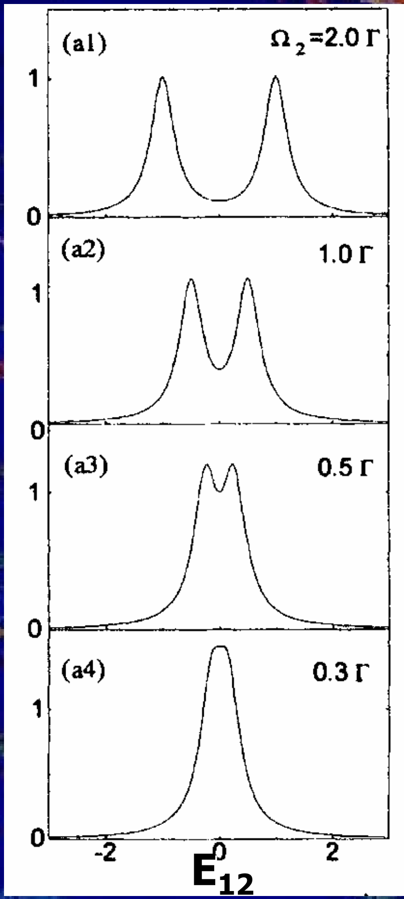
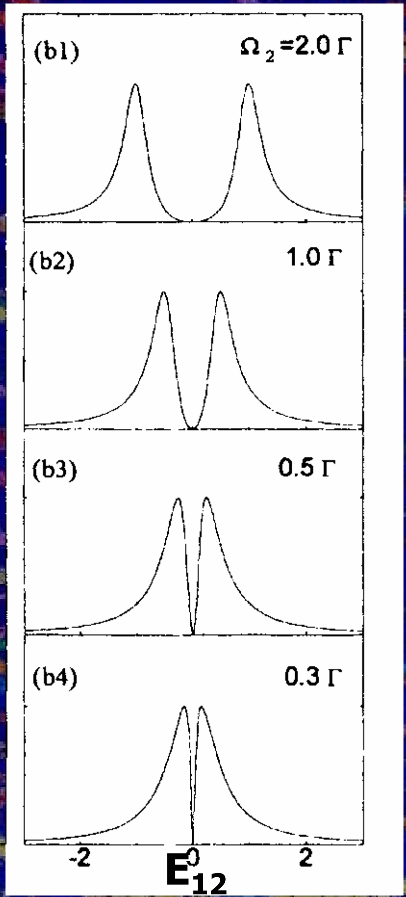
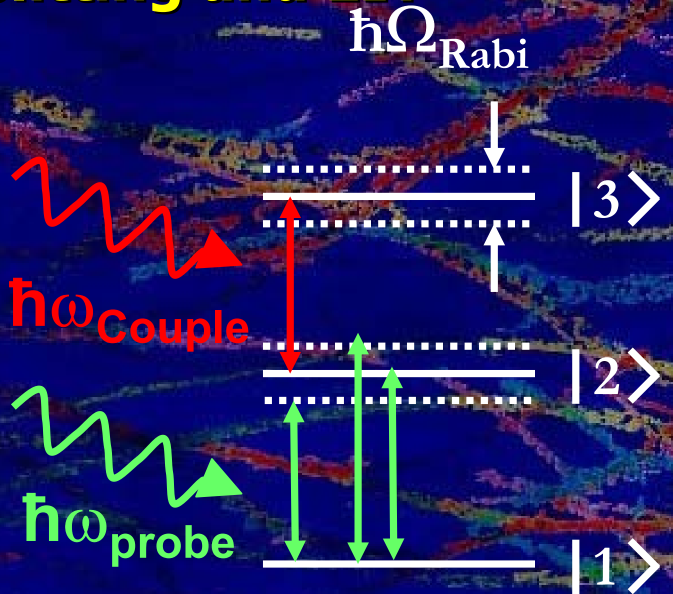
Quantum Optics: Rabi Splitting and EIT







Just the dressing

Dressing *and* Quantum Interference

Generalised Rabi Frequency

$$\hbar\Omega^2_{Rabi} = (\mu.E)^2 + (\hbar\Delta_{Couple})^2$$

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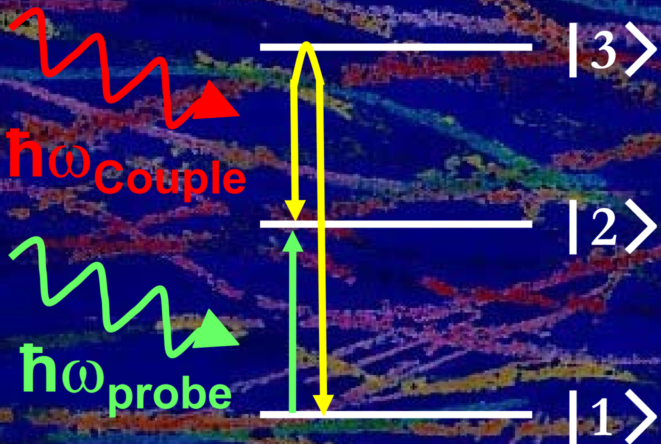
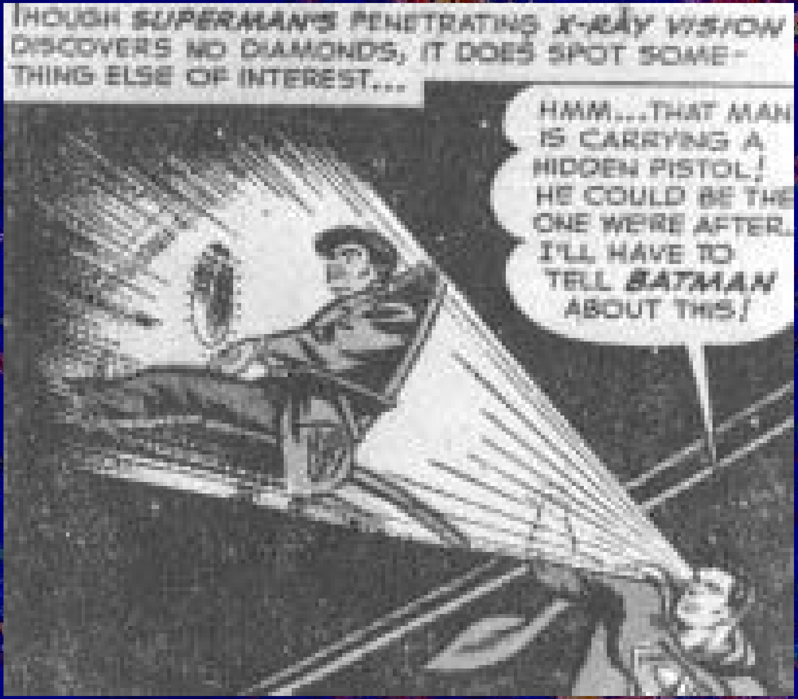
Matter-wave interference

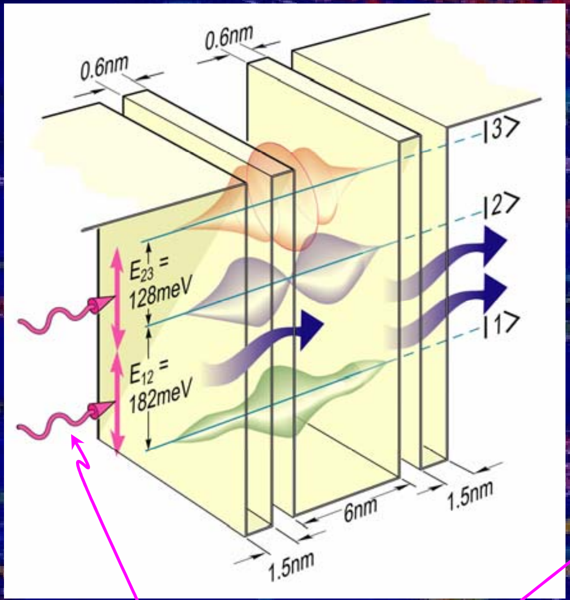


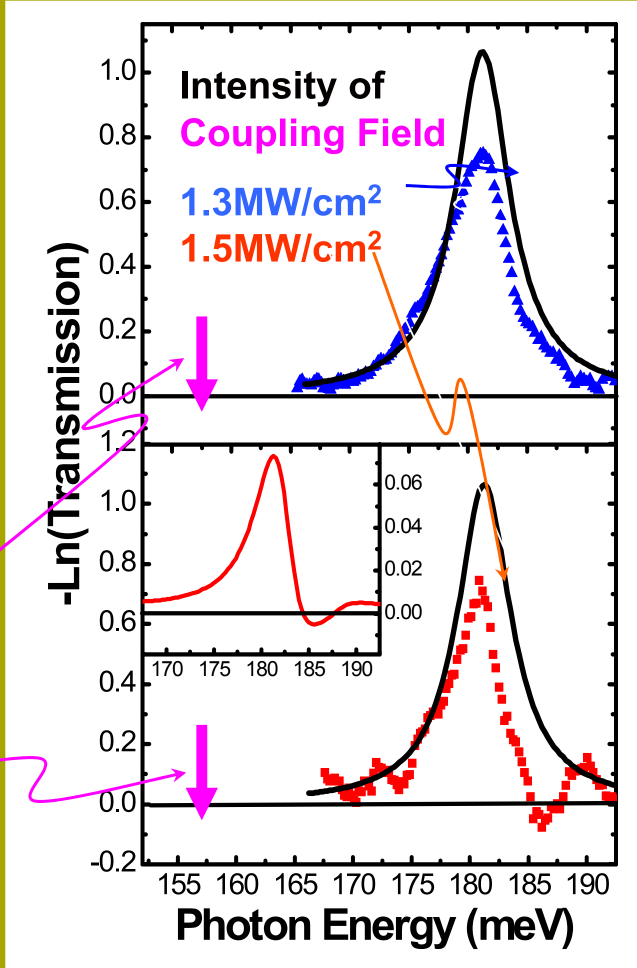
EIT was first seen in atomic vapours…



K J Boller, A Imamoglu and S E Harris, PRL 66,2593 (1991), using Rubidium vapour.

GWI with subband transitions!



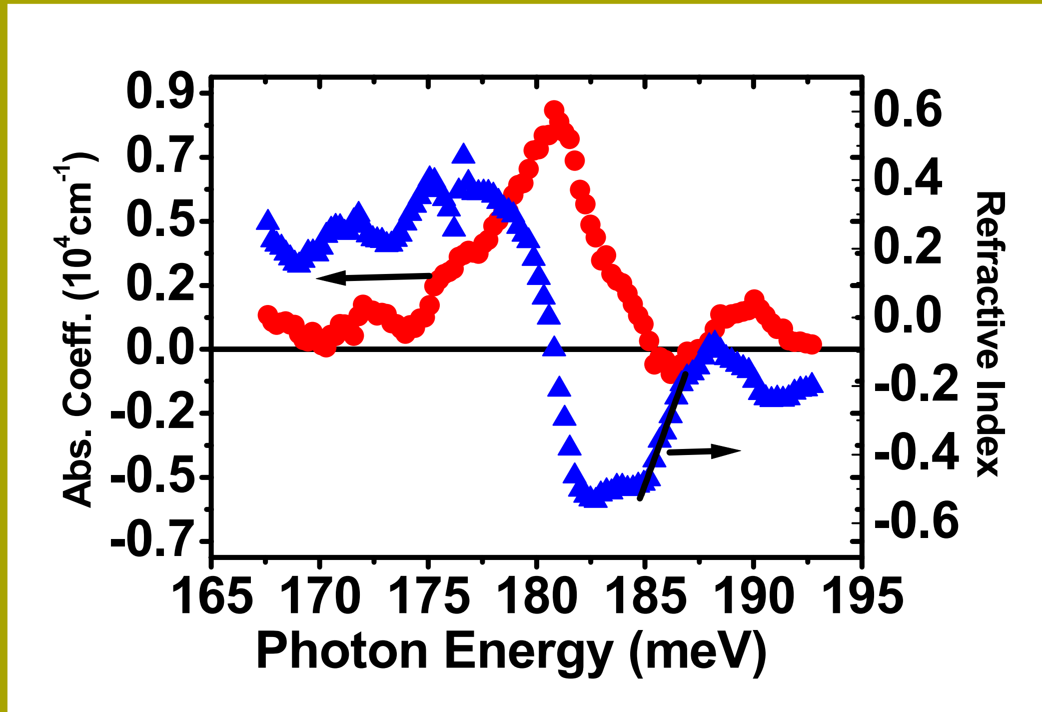


$\hbar\omega_{Couple} = 155meV$

M D Frogley et al, Nature Materials, Vol. 5 , 175-178, March 2006.

Rabi sideband expected at 155meV (= E_{couple})

Slow Light.



$V_{group} = c/n_{group} = c/(n_0 + \omega dn/d\omega)$

V_{group} = c/40 in the region where the sample is transparent/amplifying.

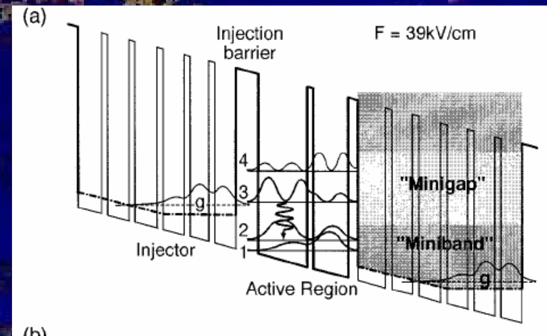
Phonon Engineering?

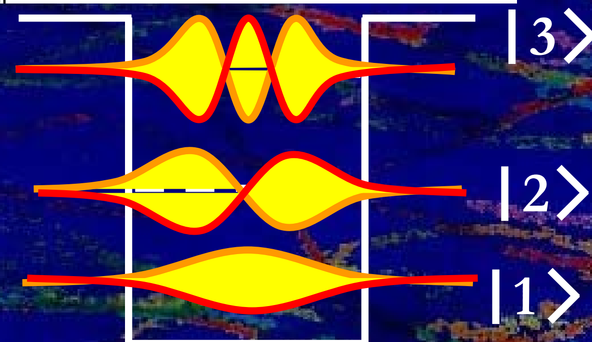
*We already structure electronics an optical aspects, why not acoustic as well?

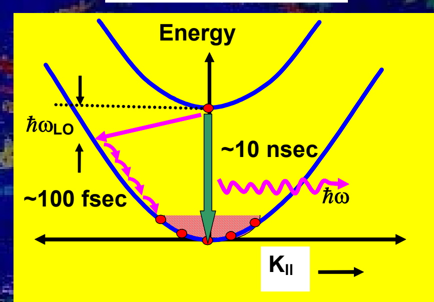
*Dephasing Acoustic and depopulating phonons both have λ~ 15 nm.

*Phononic SL's for improved thermal conductivity?

*Phononic anti-nodal cavities for decoupling electrons from crystal?







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Artificial atoms for Science!

*ISBT's behave like designable atoms

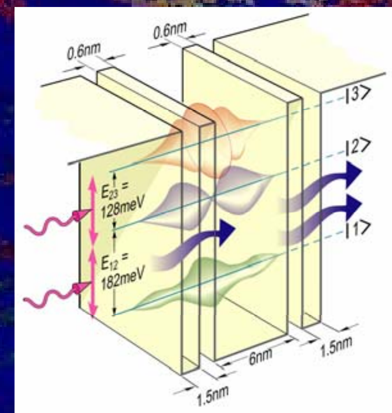
*New symmetries and energy level juxtapositions possible.

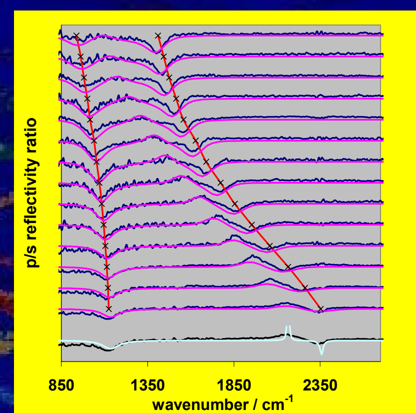
*Cavities are easy

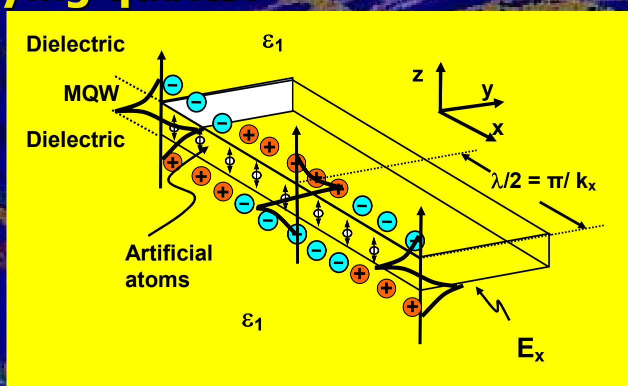
*They stay put!

*Cavity QED?

*Flying qubits?







Acknowledgements

Mark Frogley (ex-Imperial, now RAL) Jon Plumridge (Imperial) James Dynes (ex-Imperial, now UCL) Mary Matthews (Imperial) Rob Steed (Imperial)	Spectroscopy and modelling
Ed Clarke (Imperial) Ray Murray	MBE growth
H C Liu Emmanuel Dupont	Strongly coupled Cavity samples
Ben Williams (ex-MIT, now UCLA) Maurice Skolnick (Sheffield) Luke Wilson (Sheffield)	THz frequency mixing QCL's
Jerome Faist and Mattias Beck (Neuchatel)	Artificial atom multilayers
Elodie Roussard (Imperial)	DMT/Gaussian beam
Justin Rodger (Masters ICL)	AQW Design/DMT software
Danny Segal, Almut Beige (ICL)	Discussion – Dressed states

EPSRC (UK) – Funding

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