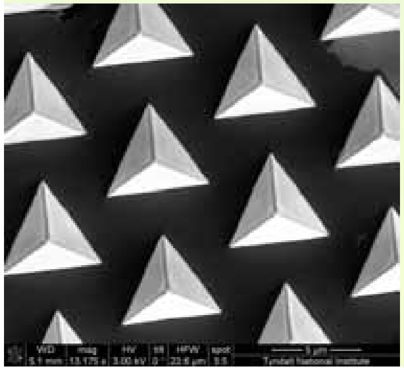
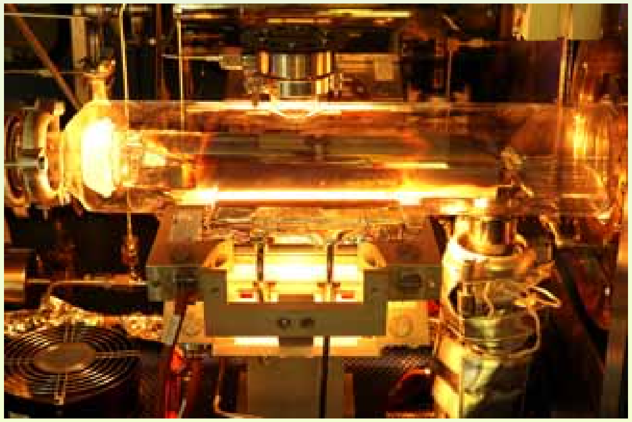
Quantum Dots and Quantum Information

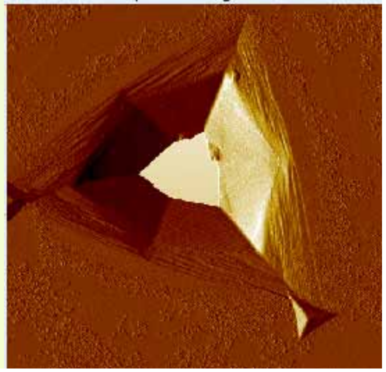
E. Pelucchi

Epitaxy and Physics of Nanostructures,
Tyndall National Institute, University College Cork,
"Lee Maltings", Prospect Row , Cork, Ireland

Group members which contributed to the experimental results:
V. Dimastrodonato (PhD), L.O. Mereni (PhD),
R.J. Young (PostDoc, left)





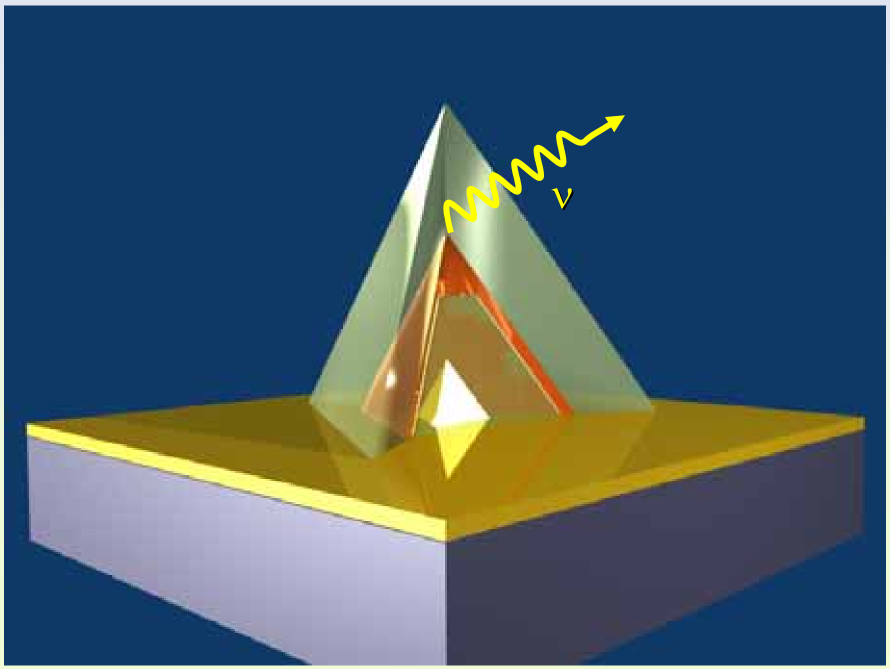


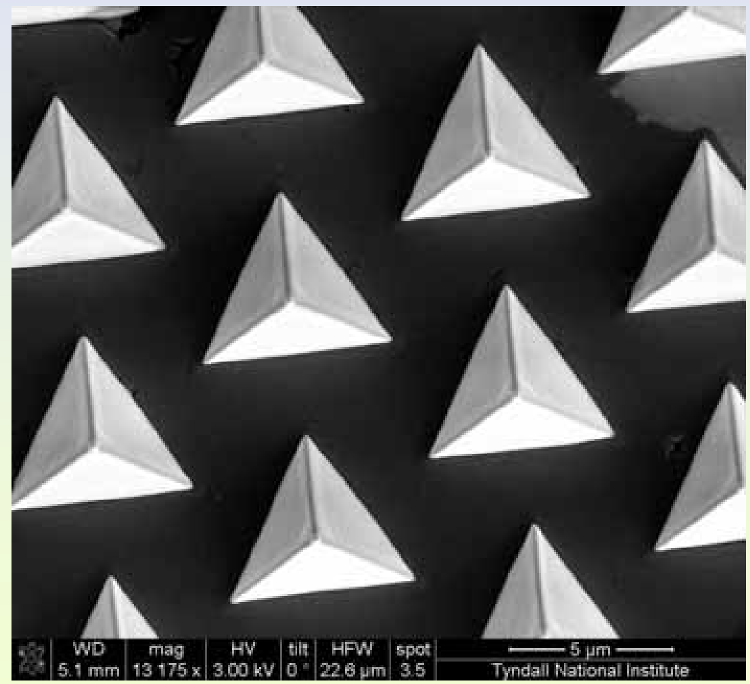
Started a new group….
1rst January 2007

SFI PI grant

Epitaxy and Physics of Nanostructures (EPN)…
a new MOVPE…

Nanoscale Engineering of Position Controlled Quantum Dot Heterostructures for Quantum Communication Processing





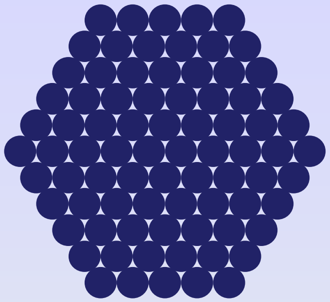
Overview

Quantum dots: the ideal picture vs reality

Overview of quantum dot research in the field of quantum information

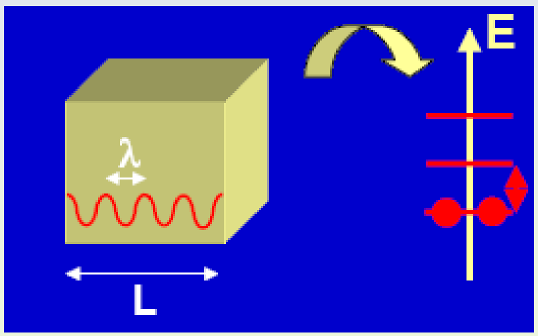
Site "controlled" QDs and EPN

QDs: the artificial atom picture

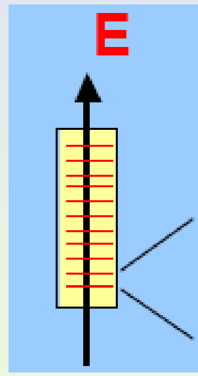


Made of thousands of atoms

Quantum Dots are often addressed as "artificial atoms": i.e. they present ***discrete energy levels.***



$$k_x L = 2 m_x \pi$$
$$k_y L = 2 m_y \pi$$
$$k_z L = 2 m_z \pi$$

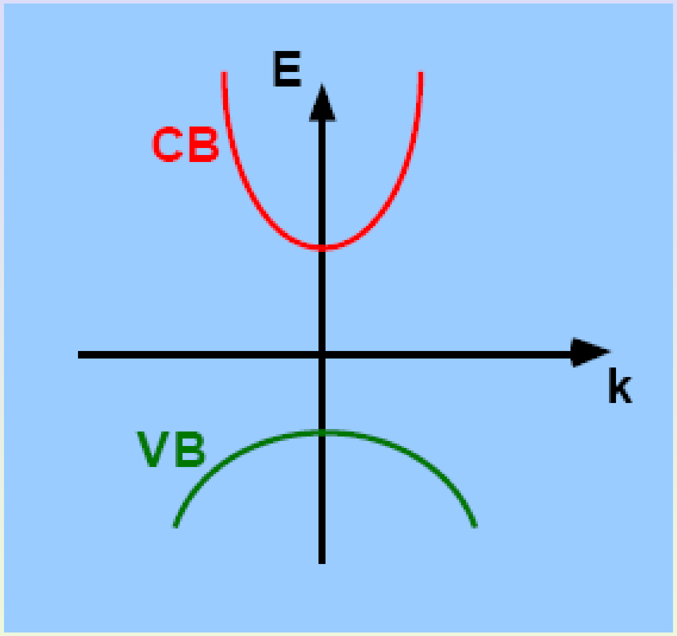


$$\Delta E \approx \frac{\hbar^2}{2m^*}\frac{4\pi^2}{L^2}$$

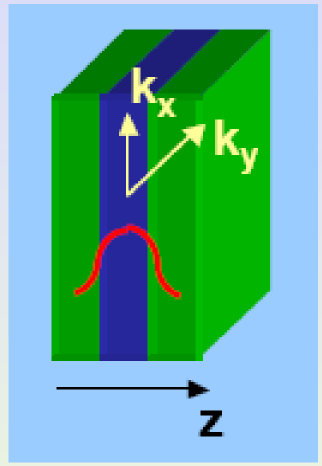
$$E = \frac{\hbar^2 k^2}{2m^*} = \frac{\hbar^2}{2m^*}\frac{4\pi^2}{L^2}\left(m_x^2 + m_y^2 + m_z^2\right)$$

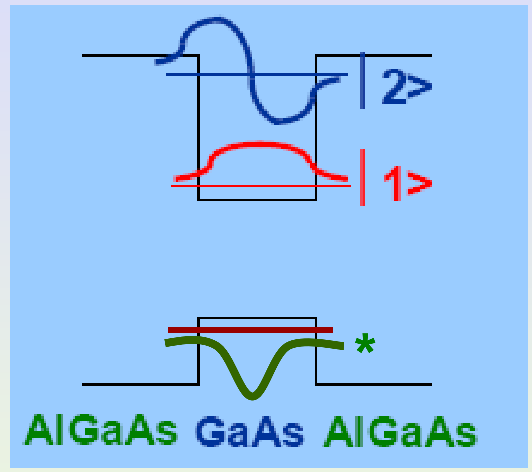
Semiconductors: not an atom

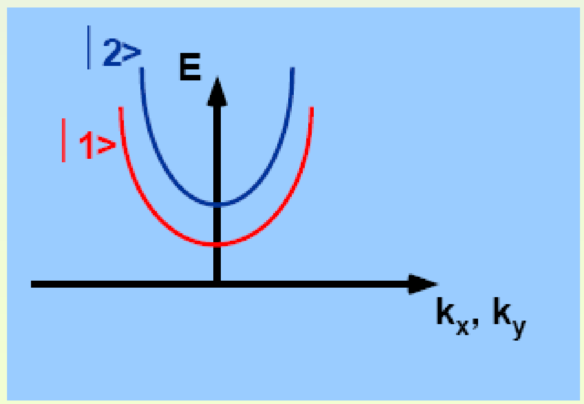
In semiconductors….



2D nanostructures, quantum wells….lasers….



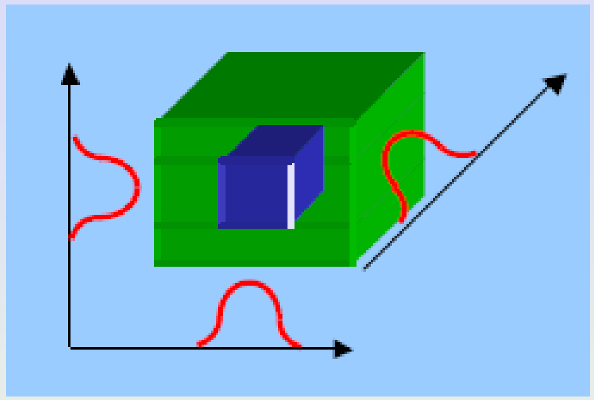


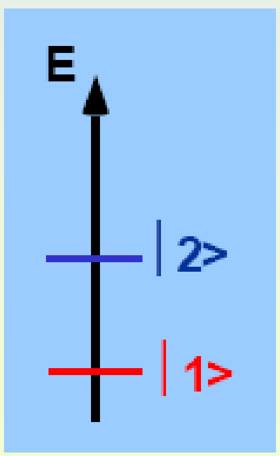


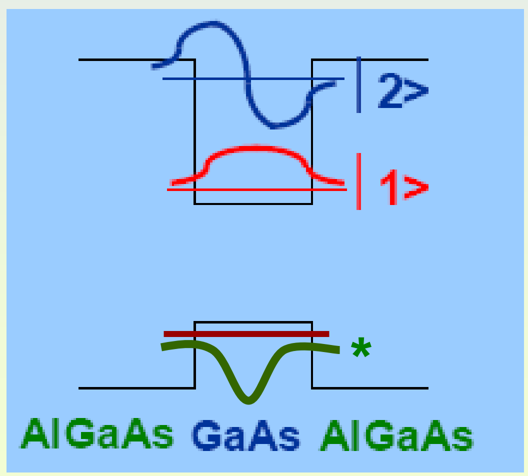
*..for the sake of discussion allow me to be a bit imprecise with the (holes) wave-functions…

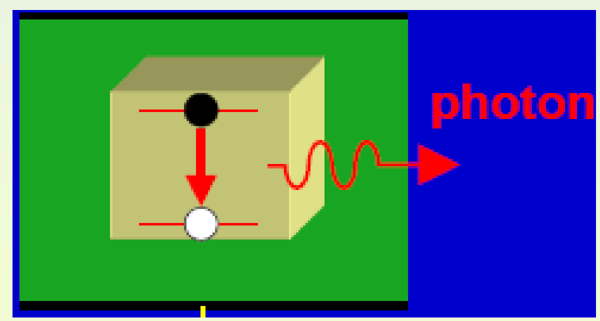
Semiconductors: not an atom II

Both electrons and holes are confined: excitons



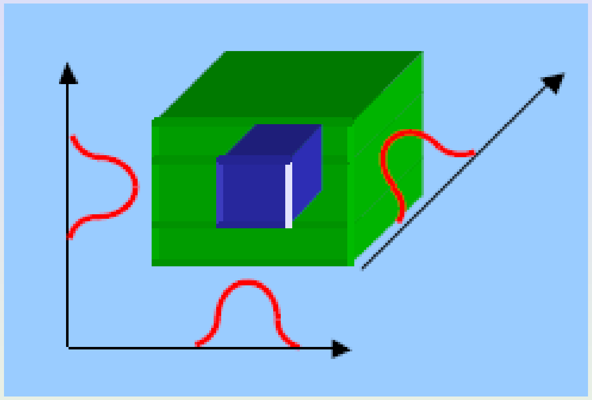






Semiconductors: not an atom III

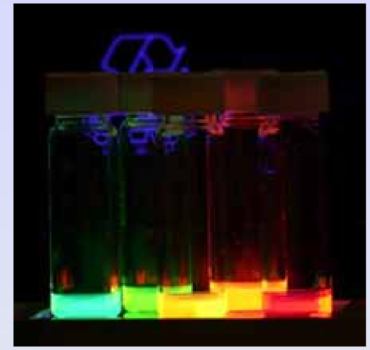
Semiconductors QDs are embedded in a matrix, which is providing the confinement: so they are not nicely isolated



Interactions:
Lattice vibration: phonons
Free charges
Ionized impurities
Strain
Interaction with nuclear spins…
………(polaritons, polarons, etc etc)

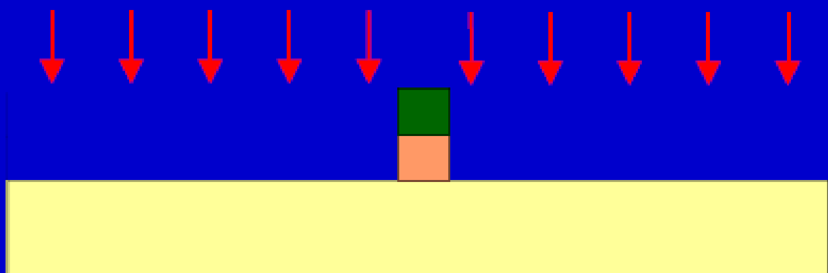
Different QD families, and methods to make them

Colloidal QDs and relatives: chemically synthesized ….nice but nor really for quantum information (a bit a personal opinion I guess)… too far yet from ideal, at least for the moment, but who knows, people are trying hard



Direct graving, etching…

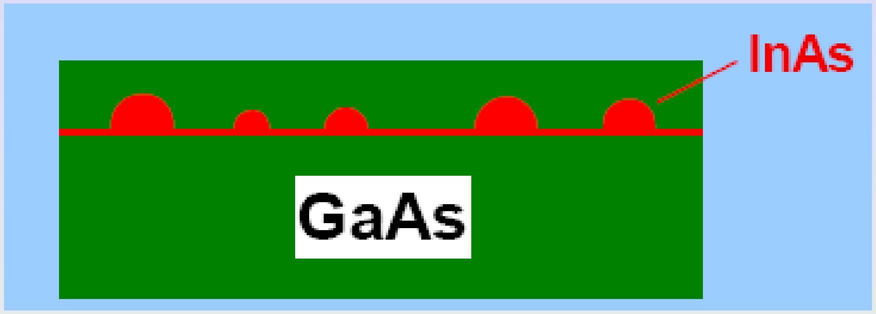
"Straightforward" approach: Fabrication on the nanoscale



- Need high-resolution lithography
- Etching ⇒ Nonradiative defects

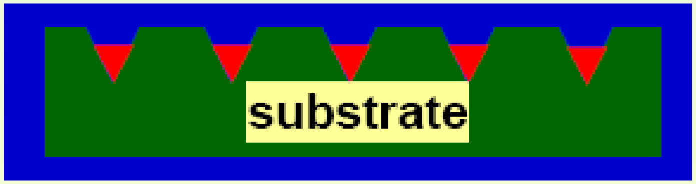
Different QD families, and methods to make them II

Self assembled QDs…from the early nineties



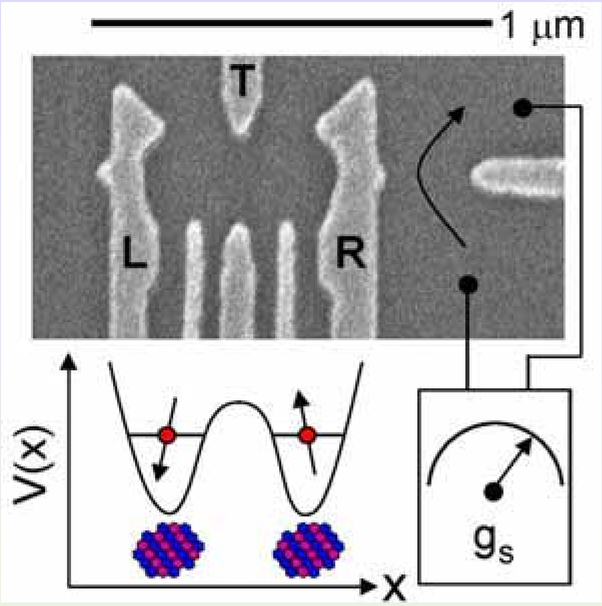
Use semiconductors which do not like to grow layer by layer on top of the others: strain-driven growth on planar substrates (SK growth)

Site controlled Pyramidal QDs…



And other combinations (dots in pillars etc etc)…between which the "transport" QDs…

Which are.....and we will not come back to them in this seminar



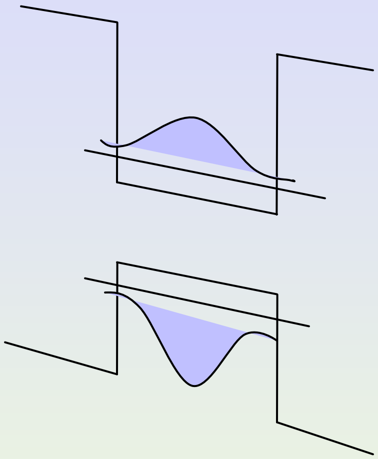
Gate defined double quantum dot fabricated from a GaAs/AlGaAs 2-dimensional electron gas wafer.

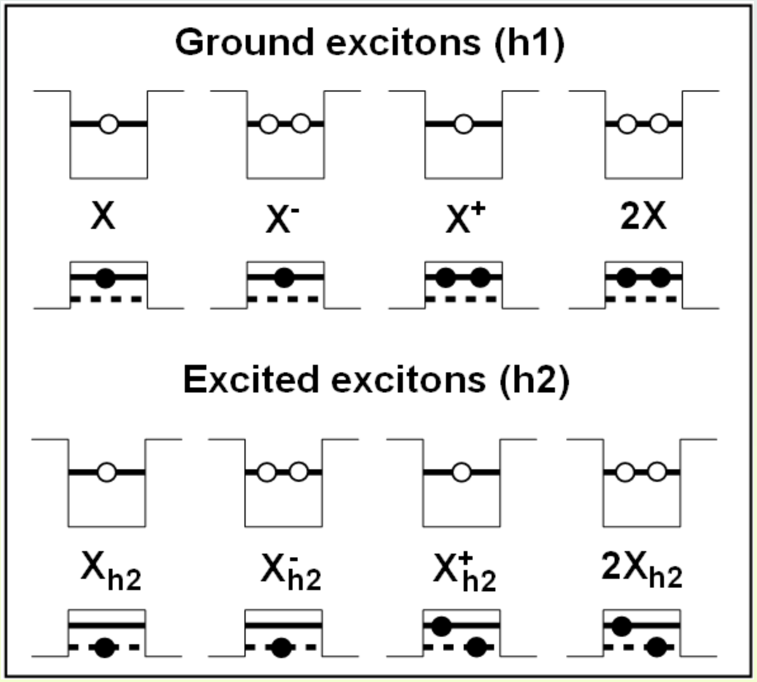
The number of electrons in the double quantum dot is determined by measuring the quantum point contact charge sensor conductance, g_S.

http://pettagroup.princeton.edu/spinqubits.html

Why QDs, and what to do with them…..but first two words on quantum dot excitons….and another difference with atoms…

You can work just with the electrons, or just the holes…and ok, more or less we are dealing with something which might look like an atom…but if you work with excitons (when dots are populated by both electrons and holes…)



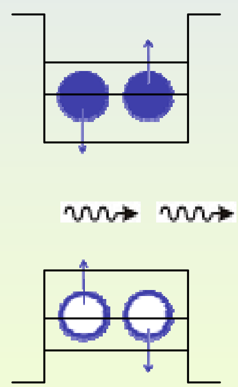


Simple sketch

Please note: the definition "exciton" here is different for an exciton in a Quantum Well. Here electron and holes are confined by the barriers…

Second level of complication….

Different charges involve different coulomb interactions: i.e. different energetic states… so, for example, an excitonic state is a single particle state (even if can be populated by both spins..)



Stealing Valeria’s slides…..

Third level of complication….

In general, dots are all quite different from each other, and not really symmetric at all (so no real pure S states, or P states….)

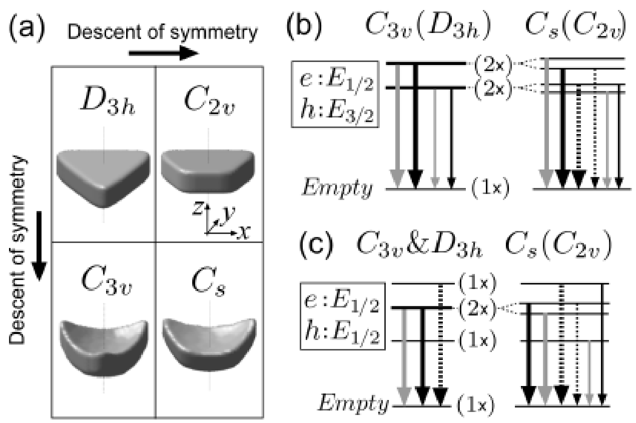


FIG. 1: (a) Symmetry hierarchy visualized by three-dimensional objects. (b and c) Polarized radiative decay paths of C_{3v} excitons formed with holes of $E_{3/2}$ and $E_{1/2}$ symmetries, and the corresponding decay of C_s excitons. Transitions forbidden under D_{3h} and C_{2v} are distinguished by thin lines and small arrows. Gray (black) lines indicate x-polarized (y-polarized) light. Dotted lines indicate z-polarized light.

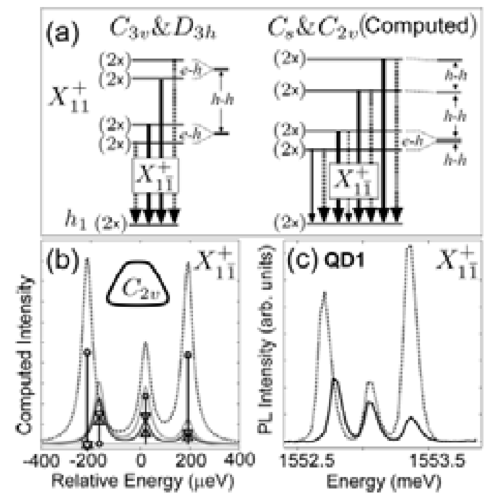


FIG. 4: (a) Polarized radiative decay paths of the positive trion X_{11} for the ideal case C_{3v} (left) and the asymmetric case C_{2v} (right). The numerical model yield dark transitions indicated by thin lines and small arrows. Black solid lines indicate both x- and y-polarized light. Dotted lines indicate z-polarized light. (b) Computed exciton spectra of $X_{1\bar{1}}$ (see caption of Fig. 3). (c) Close up PL of X_{11}.

K.F. Karlsoon et al, to be published

Why QDs, and what to do with them (to do quantum information)

Hope not to miss anything, but in general the chapters of interests can be divided into (but there are superpositions and entanglements…) :

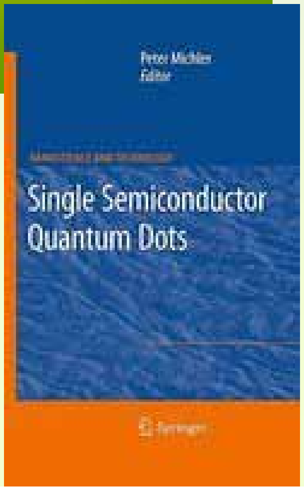
-Quantum dots as source of special photons: ”single” and “entangled”

-Use quantum dots to control electron/hole spin state, and make quantum information with these states

-QED with QDs (and this overlaps heavily with all the previous ones).

-Use quantum dot excitonic states to implement a quantum gate inside the material.. Use emitted photons o check that things are ok

A good recent review of the state of the art…. →



Special photons with QDs

Single photons

2282 22 DECEMBER 2000 VOL 290 SCIENCE

A Quantum Dot Single-Photon Turnstile Device

P. Michler,[1*] A. Kiraz,[1] C. Becher,[1] W. V. Schoenfeld,[2]
P. M. Petroff,[1,2] Lidong Zhang,[1] E. Hu,[1,2] A. Imamoğlu[1,3,4†]

Quantum communication relies on the availability of light pulses with strong quantum correlations among photons. An example of such an optical source is a single-photon pulse with a vanishing probability for detecting two or more photons. Using pulsed laser excitation of a single quantum dot, a single-photon turnstile device that generates a train of single-photon pulses was demonstrated. For a spectrally isolated quantum dot, nearly 100% of the excitation pulses lead to emission of a single photon, yielding an ideal single-photon source.

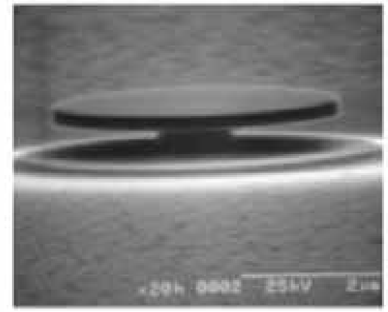


Fig. 1. The microdisk structure, which consists of a 5-µm-diameter disk and a 0.5-µm post. The GaAs disk area that supports high-quality factor WGMs is 200 nm thick and contains InAs quantum dots.

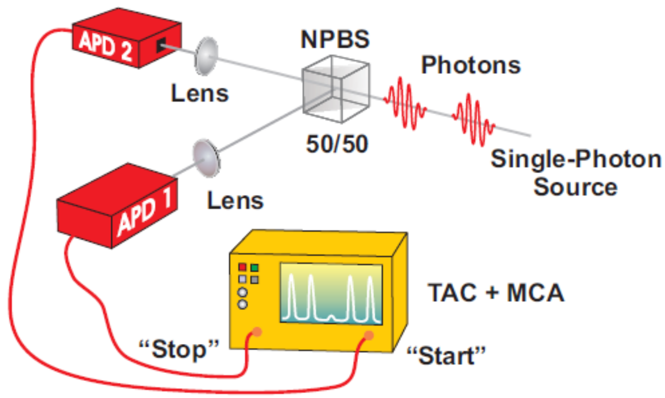


Fig. 1.10. Photon autocorrelation setup after Hanbury and Brown-Twiss. The collected photon stream from a single photon source is pre-filtered by a spectrometer (alternatively: narrow band filters) and sent to fast avalanche photo detectors (APDS) trough a 50/50 non-polarizing beamsplitter (NPBS). The photon coincidence statistics $n(\tau)$ are measured by combined time-amplitude conversion (TAC) and multi-channel analysis (MCA)

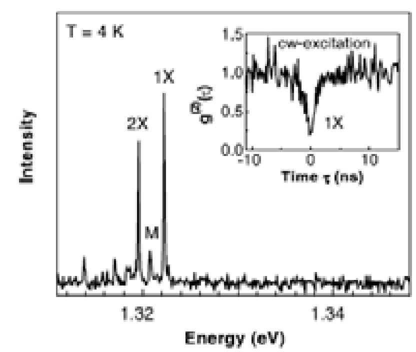


Fig. 2. Photoluminescence spectrum of a single InAs quantum dot embedded in a 5-µm-diameter microdisk. Contributions from the excitonic ground state transition (1X), higher excited states [for example, biexciton (2X)], and a WGM (M) are visible. (Inset) Measured normalized cw correlation function $g^{(2)}(\tau)$ of the single quantum dot 1X transition. The time bin is 195 ps and the excitation power is 160 W/cm^2.

Figure from: Single Semiconductor Quantum Dots (nanoscience And Technology) (2009) by Peter Michler Springer

Special photons with QDs II

Entangled photons

A semiconductor source of triggered entangled photon pairs

Nature 439, 179-182 (12 January 2006)

R. M. Stevenson[1], R. J. Young[1,2], P. Atkinson[2], K. Cooper[2], D. A. Ritchie[2] & A. J. Shields[1]

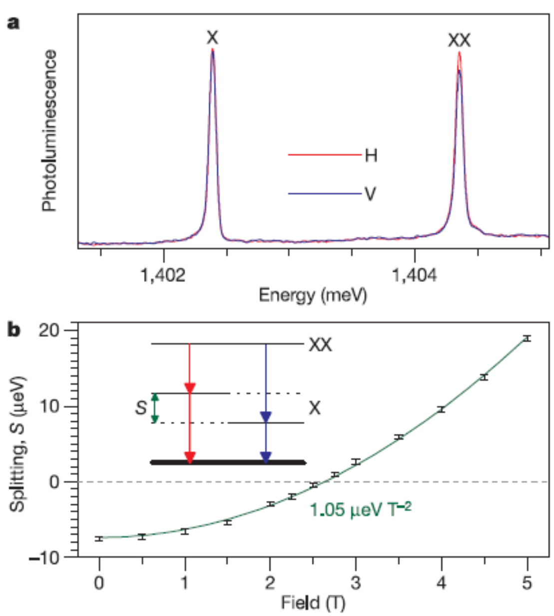


Figure 1 | Polarized photoluminescence spectra from single quantum dots. **a**, Vertically (blue) and horizontally (red) polarized photoluminescence for a single quantum dot with small polarization splitting. The features correspond to emission by the exciton (X) and biexciton (XX) state. **b**, Polarization splitting, *S*, as a function of in-plane magnetic field for a single dot with 'inverted' *S* at 0 T. The green line shows a quadratic fit to the data with a coefficient of 1.05 μeV T^{-2}. Inset shows the level diagram of the radiative decay of the biexciton state. The competing two photon decay paths are distinguished only by the polarization of the photons, indicated by the arrow colour, and the splitting, *S*, of the intermediate exciton level. Error bars span two standard deviations from the fitted line.

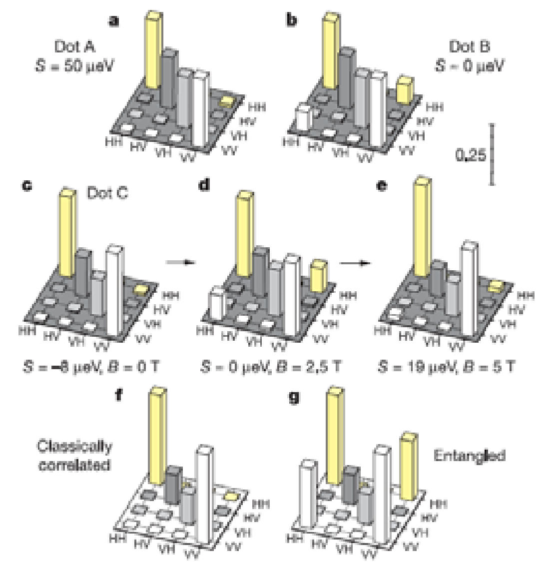


Figure 3 | Density matrices for the biexciton–exciton two-photon cascade from conventional and degenerate quantum dots. **a–e**, Real parts of measured density matrices corresponding to reference dot A with polarization splitting, $S = 50\,\mu eV$ (**a**), dot B with $S \approx 0\,\mu eV$ at 0 T (**b**), and dot C, with *S* tuned by the magnetic field to be −8 μeV (**c**), 0 μeV (**d**) and 19 μeV (**e**). The imaginary components are not shown, and were zero within experimental error. Density matrices **b** and **d** feature strong outer off diagonal elements associated with entangled photon pair states, which are not present in the reference case (a). **f**, **g**, Density matrices representing the predicted state for ideal classically correlated (**f**) and entangled (**g**) photon pairs, including 50% contribution from uncorrelated background light.

Why?

Because one can make a quantum computer just with single photons/entangled photons and beam splitters/detectors, filters and little more..

***Read for example this review: Science* 318, 1567 (2007);**

Jeremy L. O'Brien, Optical Quantum Computing

In 2001, all-optical quantum computing became feasible with the discovery that scalable quantum computing is possible using only single-photon sources, linear optical elements, and single-photon detectors. Although it was in principle scalable, the massive resource overhead made the scheme practically daunting. However, several simplifications were followed by proof-of-principle demonstrations, and recent approaches based on cluster states or error encoding have dramatically reduced this worrying resource overhead, making an all-optical architecture a serious contender for the ultimate goal of a large-scale quantum computer. Key challenges will be the realization of high-efficiency sources of indistinguishable single photons, low-loss, scalable optical circuits, high-efficiency single-photon detectors, and low-loss interfacing of these components.

Idea: why not do it on an optical table but in an integrated device? (not mine unfortunately..)

QDs and spins

Spin is a good degree of freedom for an electron /hole in a QD, and there are several proposal on how to implement quantum gates…
The spin has a relatively long lifetime, but it "feels " the nuclear spins of the nucleus (thousands of little magnets) and tends to decohere… remarkably it is actually possible to control the nuclear spins by optical means….

Breakdown of the nuclear-spin-temperature approach in quantum-dot demagnetization experiments

***Nature Physics* 5**, 407-411 (10 May 2009)

P. Maletinsky*, M. Kroner and A. Imamoglu*

the nuclear spins. Strain-induced, inhomogeneous quadrupolar shifts also lead to a complete suppression of angular-momentum exchange between the nuclear-spin ensemble and its environment, resulting in nuclear-spin relaxation times exceeding an hour. Remarkably, the position-dependent axes of the quadrupolar interactions render magnetic-field sweeps inherently non-adiabatic, thereby causing an irreversible loss of nuclear-spin polarization.

QED with QDs: polaritons

Nature **445**, 896-899 (2007)

Quantum nature of a strongly coupled single quantum dot–cavity system

K. Hennessy[1,2*], A. Badolato[1*], M. Winger[1*], D. Gerace[1], M. Atatüre[1], S. Gulde[1], S. Fält[1], E. L. Hu[2] & A. Imamoğlu[1]

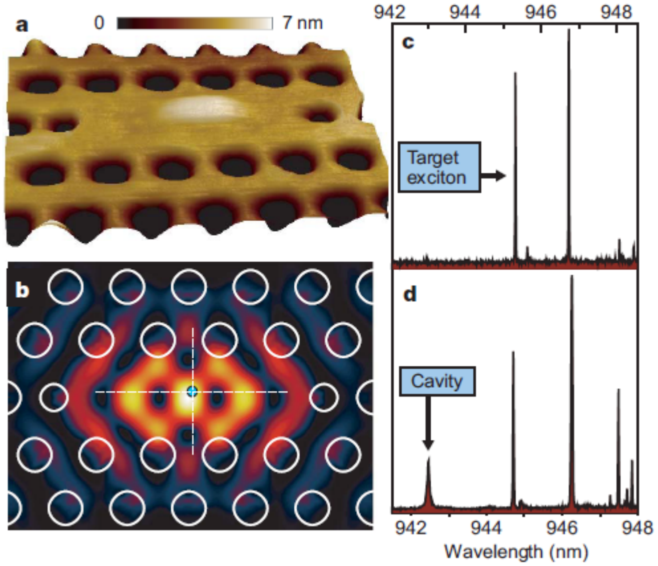


Figure 1 | Positioning a photonic crystal cavity mode relative to a single buried QD. a, AFM topography of a photonic crystal nanocavity aligned to a hill of material on the surface arising from a QD buried 63 nm below. The height scale is depicted by the colour bar. **b,** Electric field intensity of the photonic crystal cavity mode showing that the location of the buried QD, indicated by the teal dot, overlaps the field maximum. The field intensity ranges from zero (black) to a maximum (white), going through blue, red and yellow. **c,** Photoluminescence spectrum before cavity fabrication of a single QD, which was selected for cavity coupling on the basis of clear emission from a few discrete excitonic transitions. **d,** Photoluminescence spectrum from the same QD after cavity fabrication, showing emission from the cavity at 942.5 nm.

the cavity is tuned by a thin-film condensation technique

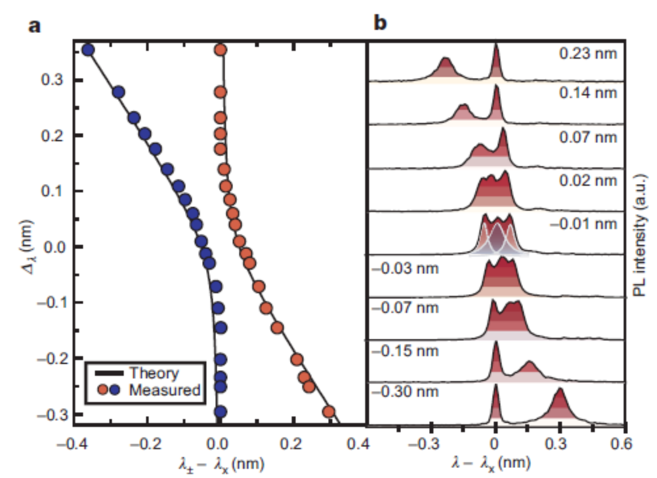


Figure 3 | Characteristics of the strong-coupling regime in the spectral domain. a, Wavelength of the polaritons for various detunings, Δ_λ. Calculated spectral peak positions describing the strongly coupled system are plotted as solid lines, with measured peak positions extracted from photoluminescence plotted in red and blue dots. **b,** Spectra of the two anticrossing polariton states near zero detuning. An additional peak is identified as the pure photonic state of the cavity. Values of Δ_λ are shown for each spectrum. PL, photoluminescence; a.u., arbitrary units.

Next step: two or more QDs….and coupling to waveguides.. to make a quantum circuit..

Or mixing up ideas and concepts….

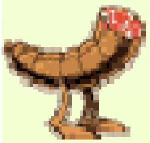
VOLUME 83, NUMBER 20 PHYSICAL REVIEW LETTERS 15 NOVEMBER 1999

Quantum Information Processing Using Quantum Dot Spins and Cavity QED

A. Imamoḡlu,[1,2] D. D. Awschalom,[2] G. Burkard,[3] D. P. DiVincenzo,[4] D. Loss,[3] M. Sherwin,[2] and A. Small[2]
[1]*Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106*
[2]*Department of Physics, University of California, Santa Barbara, California 93106*
[3]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[4]*IBM Research Division, T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*
(Received 27 April 1999; revised manuscript received 15 July 1999)

The electronic spin degrees of freedom in semiconductors typically have decoherence times that are several orders of magnitude longer than other relevant time scales. A solid-state quantum computer based on localized electron spins as qubits is therefore of potential interest. Here, a scheme that realizes controlled interactions between two distant quantum dot spins is proposed. The effective long-range interaction is mediated by the vacuum field of a high finesse microcavity. By using conduction-band-hole Raman transitions induced by classical laser fields and the cavity-mode, parallel controlled-not operations, and arbitrary single qubit rotations can be realized.

PACS numbers: 03.67.Lx, 42.50.Dv, 73.61.–r



This paper has more than 800 citations…

QDs and quantum gates: coupled QDs for example

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Conditional Quantum Dynamics and Logic Gates

Adriano Barenco, David Deutsch, and Artur Ekert
Clarendon Laboratory, Physics Department, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

Richard Jozsa
School of Mathematics and Statistics, University of Plymouth, Plymouth PL4 8AA, United Kingdom
(Received 21 September 1994)

Quantum logic gates provide fundamental examples of conditional quantum dynamics. They could form the building blocks of general quantum information processing systems which have recently been shown to have many interesting nonclassical properties. We describe a simple quantum logic gate, the quantum controlled-NOT, and analyze some of its applications. We discuss two possible physical realizations of the gate, one based on Ramsey atomic interferometry and the other on the selective driving of optical resonances of two subsystems undergoing a dipole-dipole interaction.

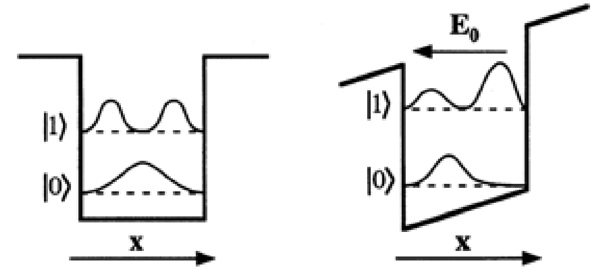


FIG. 1. Charge density in the quantum well in the direction **x** of the applied field. A dipole moment is induced when the electric field is turned on (b), but is zero without the electric field (a).

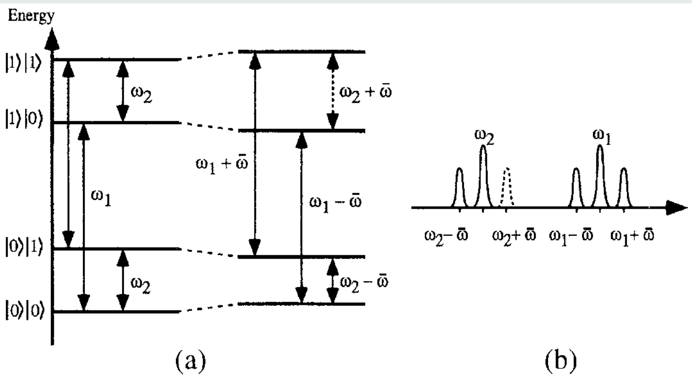


FIG. 2. (a) Energy levels of two quantum dots without and with the coupling induced by the presence of a static electric field $\mathbf{E}_0$. (b) Resonance spectrum of the two quantum dots. The dotted line shows the wavelength for which the two dots act as a controlled-NOT gate, with the first dot being the control qubit and the second the target qubit.

This is not what people are thinking do to exactly…but never the less all the basic ideas are there…

It is difficult to get all the parameters right: The dots, the dipole, the electronic states, the coupling etc

Site “controlled” QDs and EPN

Infrastructure: the MOVPE, an 8.5 meters machine

Double reactor set-up: single wafer for high purity and 3x2inch for device growths

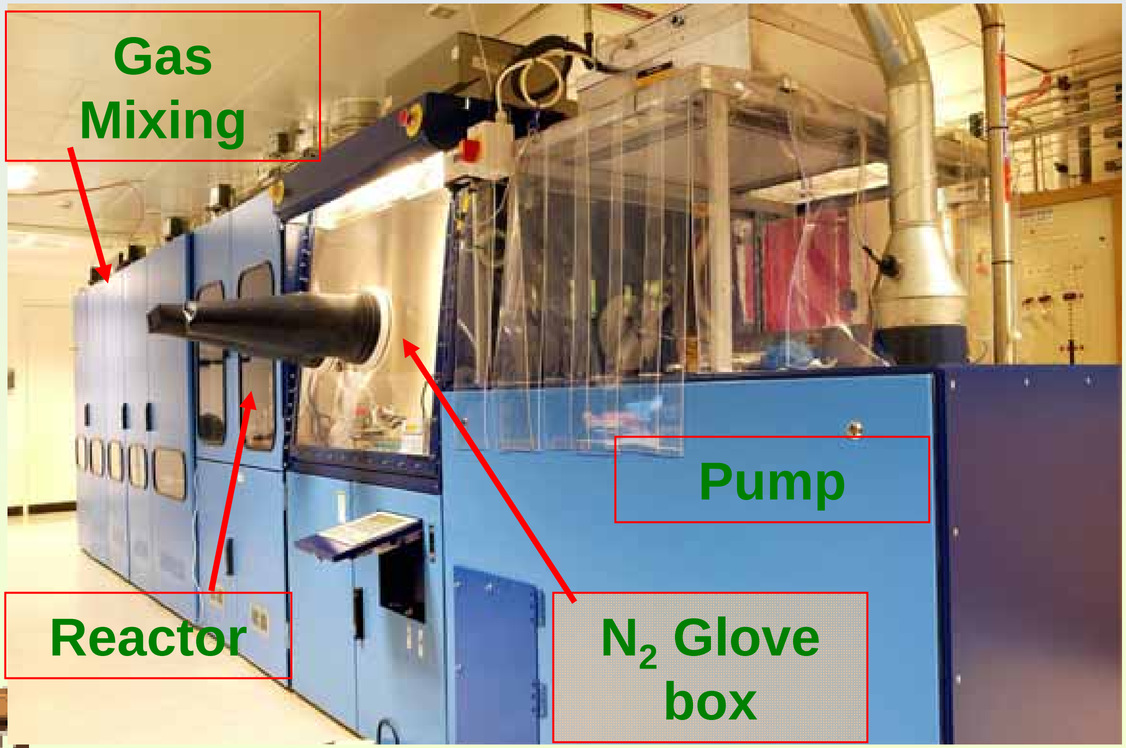
Carrier gas is nitrogen

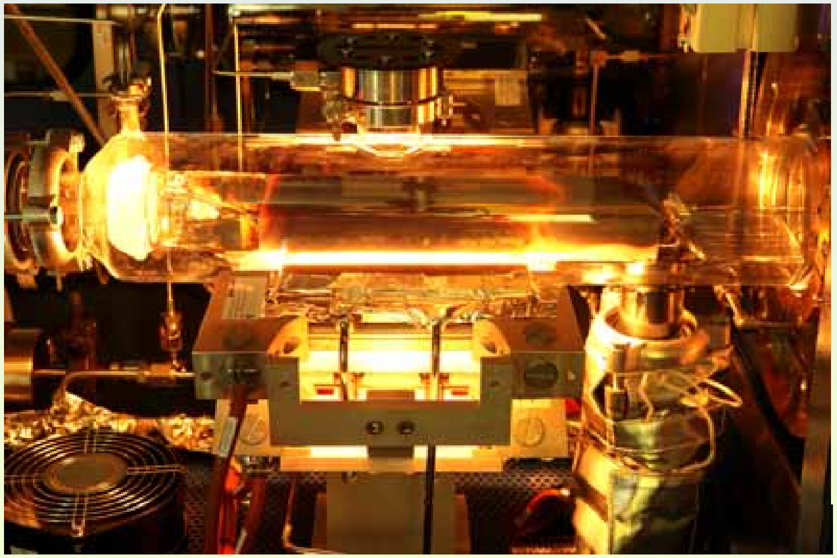
Double gas purification

Working pressure 20-80 mbar

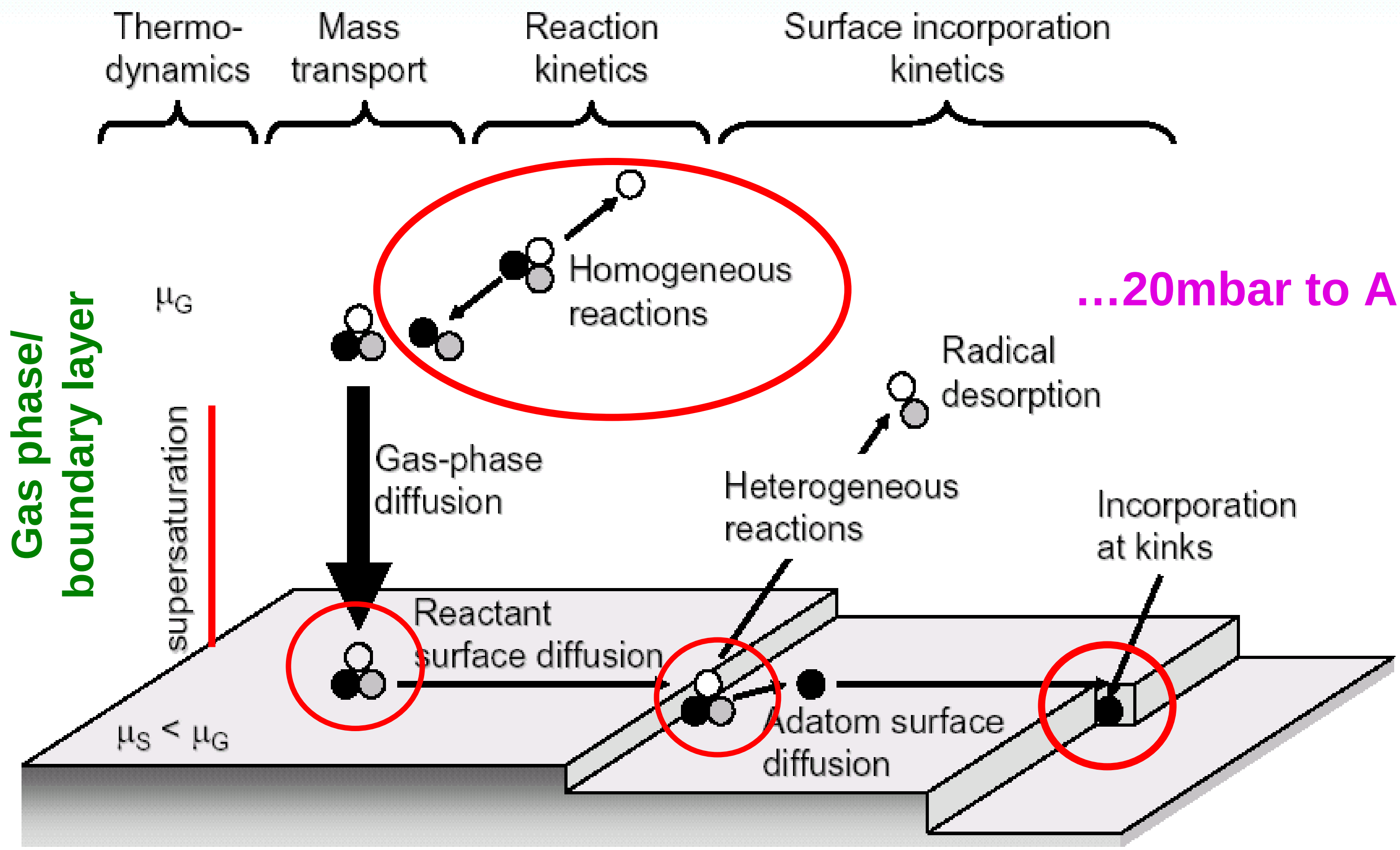
Broad choice of sources: 11 bubblers ….

Dedicated "dopants" line for Zn……





The MOVPE growth process



…20mbar to AP

Precursors

TMGa

TMAl

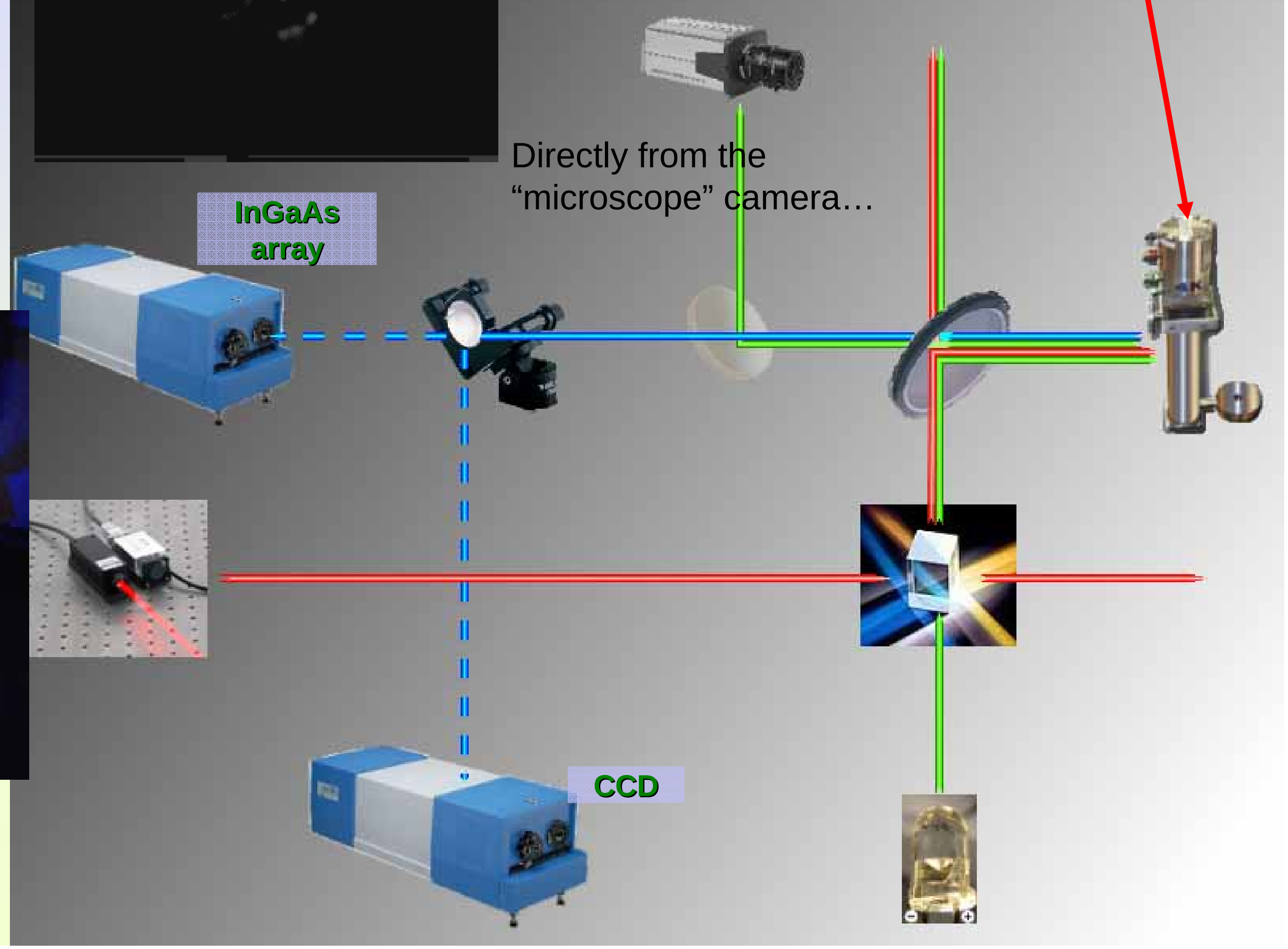
AsH_3

Decomposition happens in steps: $Ga(CH_3)_3 = Ga(CH_3)_2 + CH_3$

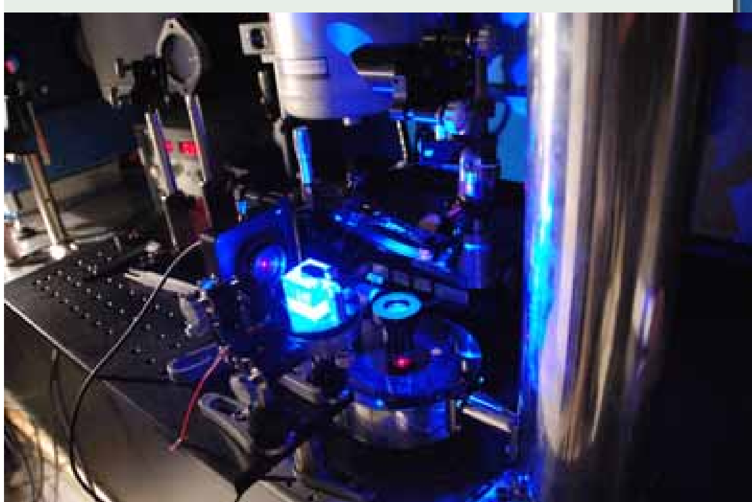
Infrastructure : the micro-photoluminescence

Building the photon correlation set-up…

Low vibration, low Temperature (7K) Closed cycle cryostat



Two spectrometers: one CCD and one InGaAs array



Nanoscale Engineering of Position Controlled Quantum Dot Heterostructures for Quantum Communication Processing

SK dots

Self organized QDs: Stranski-Krastanow

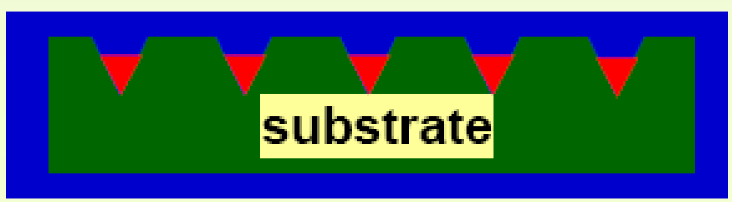
We want to control the properties of semiconductor QDs…..

We want to control the position

We want to control the wavefunction

We want to control how many we put….

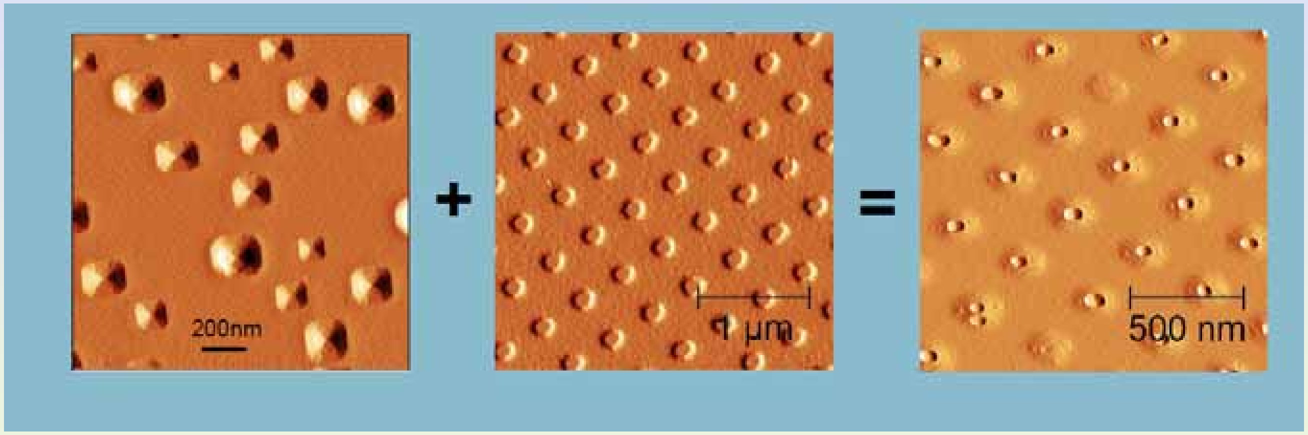
We want to make the way we need them…..and we want them *very good*…



We give nature a hand…

The Pyramids idea and concept……..

It is not a combination of self assembling (SK) and patterning



It is the 3D version of quantum wires…..(V-grooves)

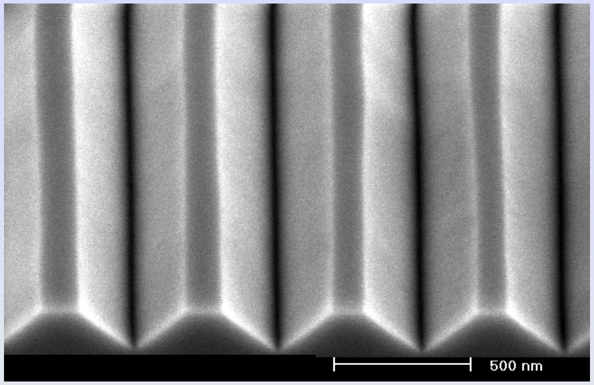
- QWR (100) or QD (111)B

- Wet chemical etching using photo and electron-lithographical methods

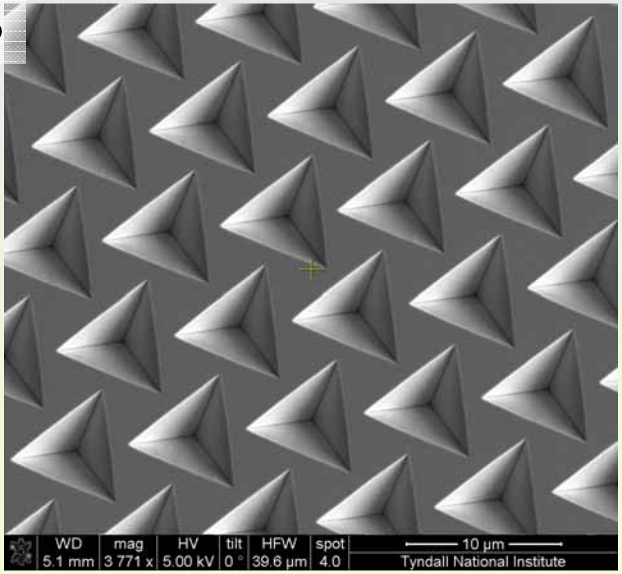
- MOVPE deposition of (In)GaAs/AlGaAs or InGaAs/GaAs…

SEM

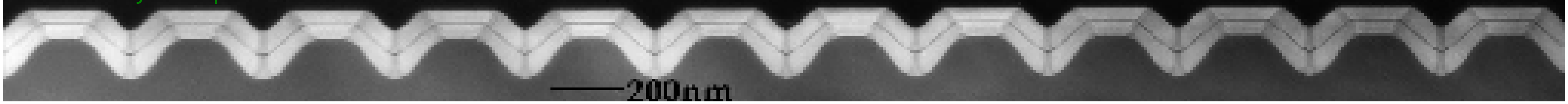
(100)



(111)B

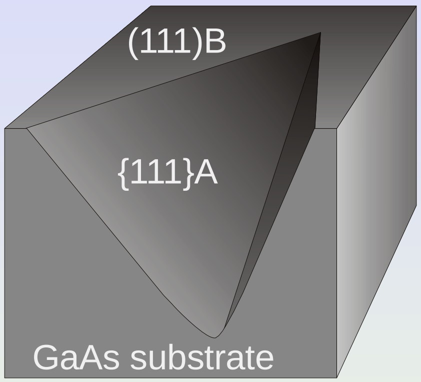


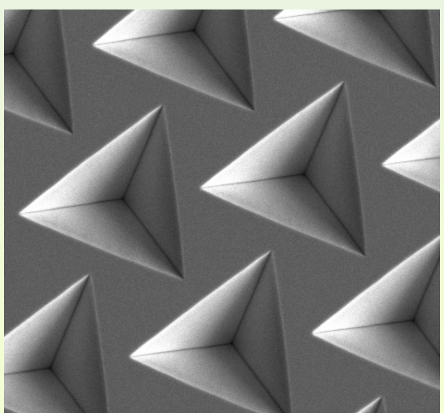
Courtesy E. Kapon



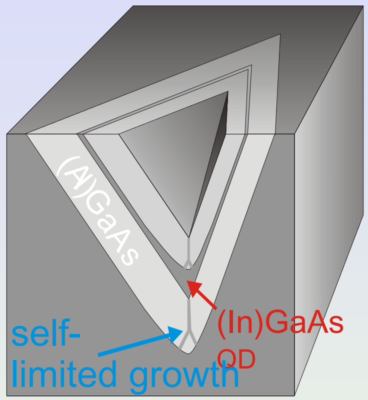
Pyramids : lithography, growth , post processing

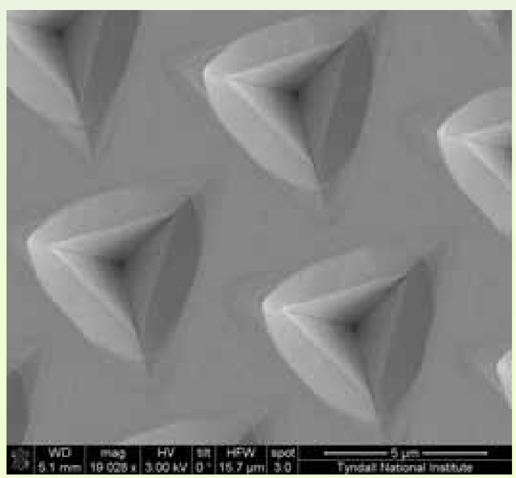
(111)B substrate patterning



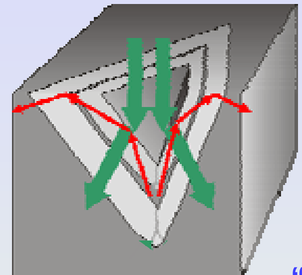


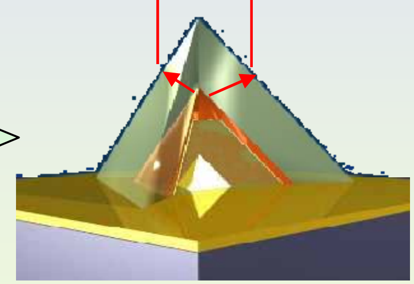
MOVPE growth



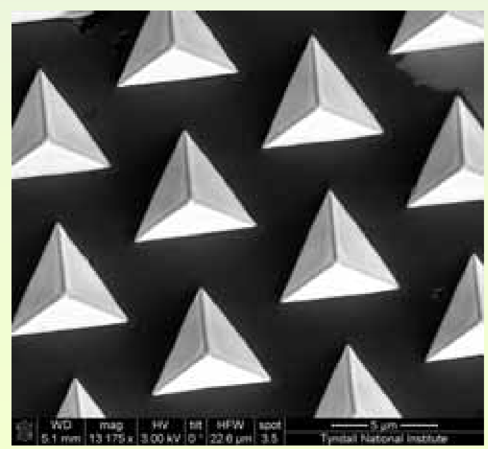


Post processing to enhance extraction



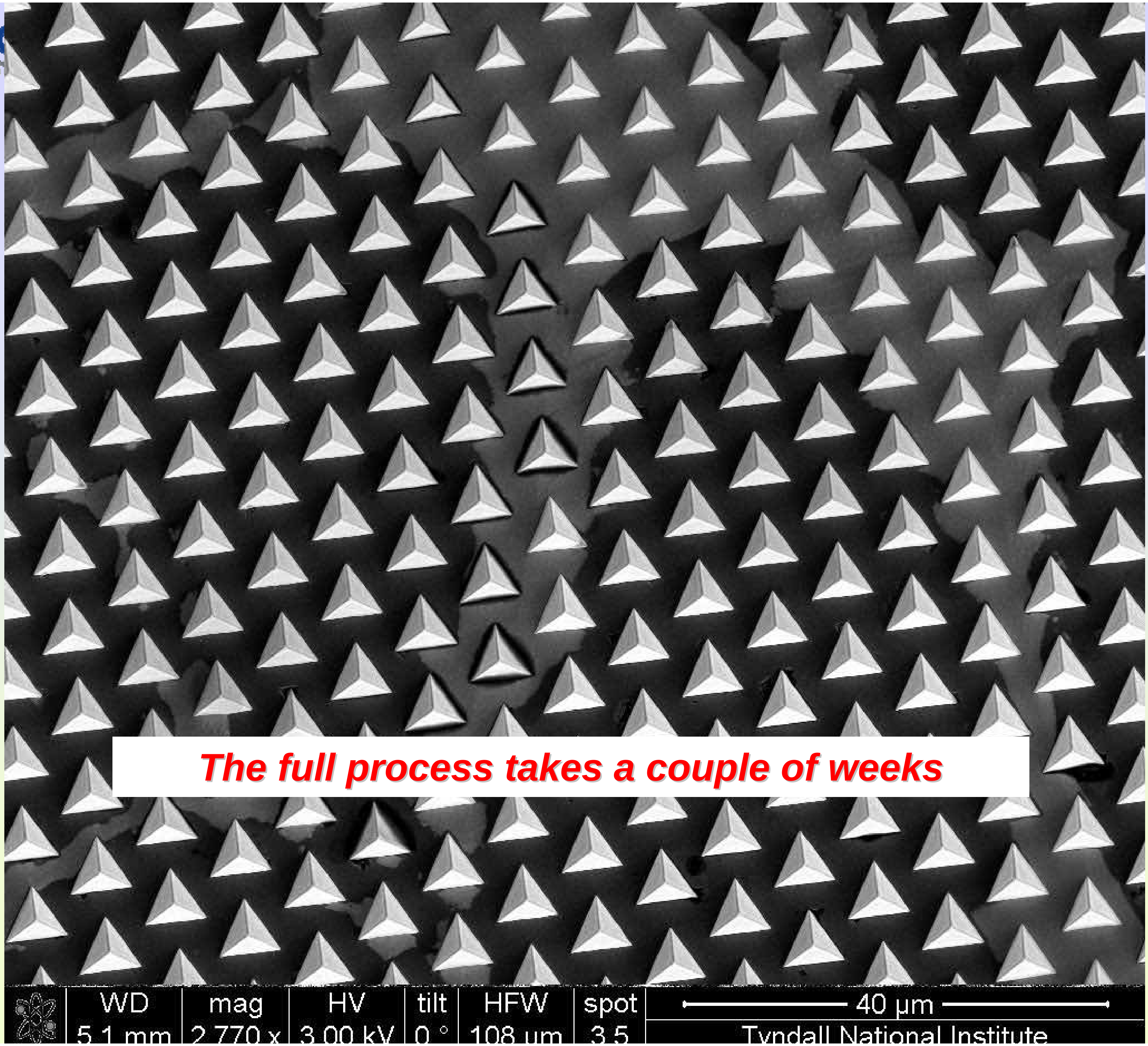


"apex up" or "back etching"



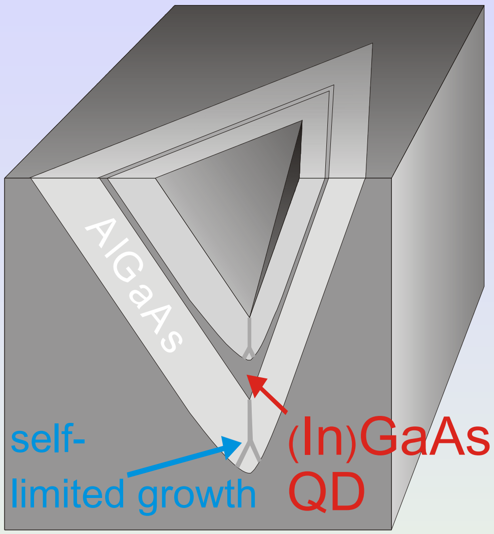
This SEM picture will be there to indicate when we performed μPL spectra in "apex-up " geometry

A nice picture: after the substrate removal

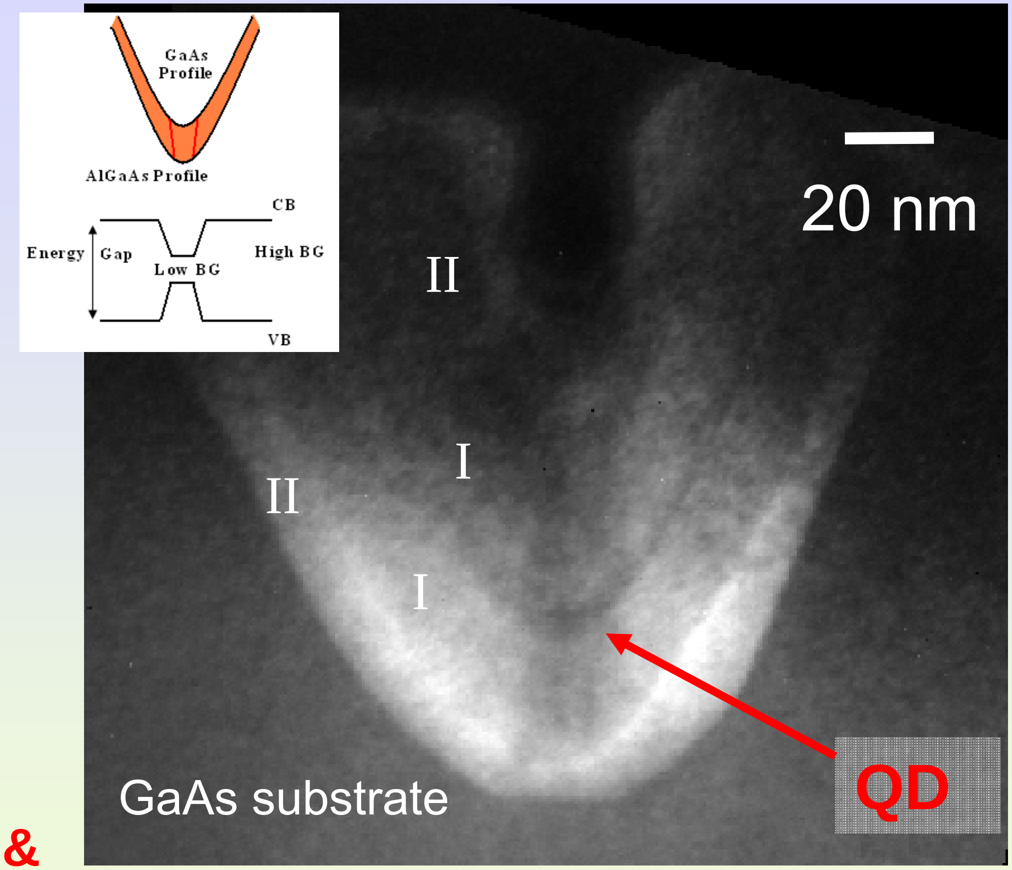


The full process takes a couple of weeks

Pyramidal QD formation



capillarity



Simple growth: *design resembles 2D quantum well growth*

Position control: substrate patterning &

self limiting

seeded MOVPE (*as in v-grooves*)*

GaAs QD,
in 30% AlGaAs barriers (I) and
55% AlGaAs claddings (II) (nominal)**

*G. Biasiol and E. Kapon, Phys. Rev. Lett. **81**, 2962 (1998).

**K. Leifer, E. Pelucchi, S. Watanabe, F. Michelini, B. Dwir, and E. Kapon to be published

Why is purity important?

Background doping influences heavily the dot linewidth; spectral meandering

If the background doping is too high, no clear evidence of dot signatures: this is particularly dramatic in the Pyramidal QD system

Spectral meandering can be linked to decoherence (only to some extent: different timescales)

Spectral meandering is detrimental when QDs are inserted in quantum electrodynamics cavities (photonic crystals , micro pillars)

Quantum gates require as ideal a dot state as it can be…..

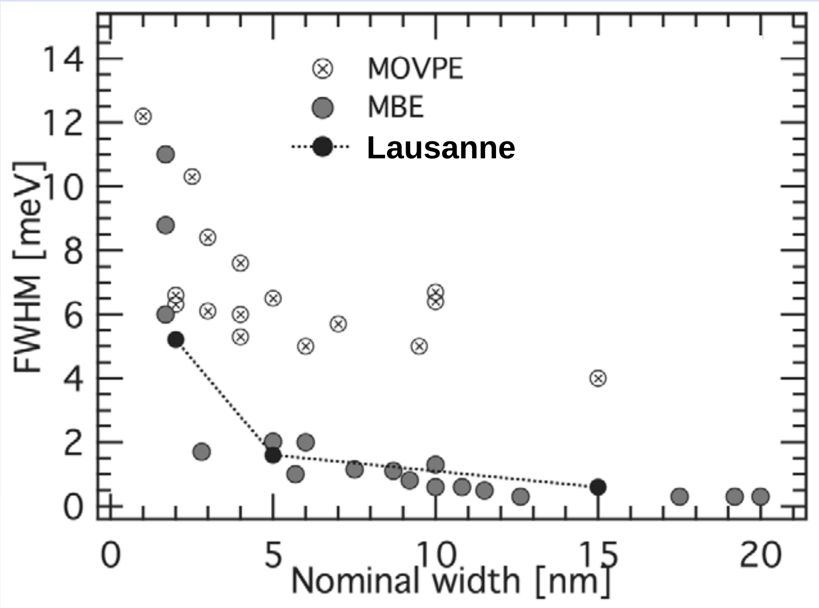
Dot reproducibility: it also involves being reproducible in the multiexcitonic states …..charged dot vs neutral

…….

Typically MOVPE is outperformed by MBE

MOVPE normally is not as good as MBE…

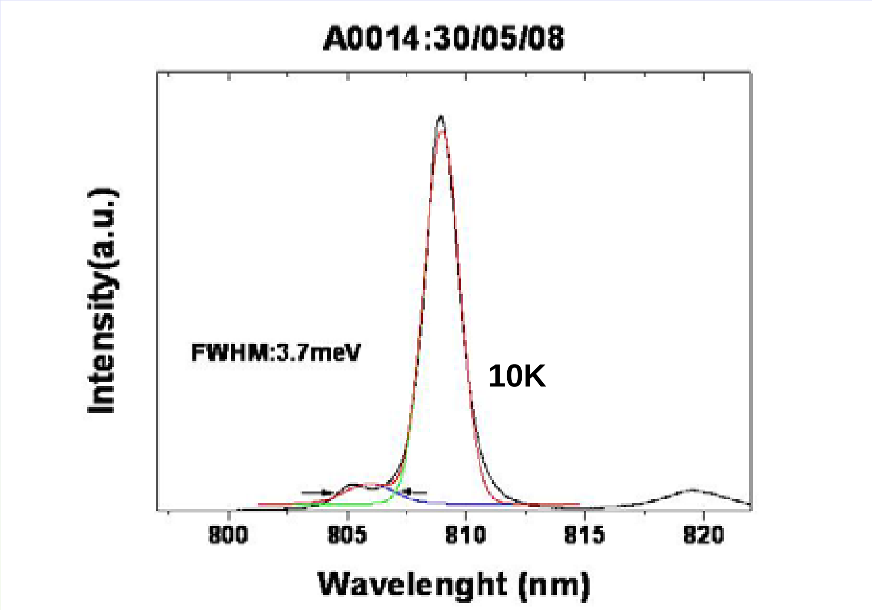
Comparing with published data…..



N. Moret et al unpublished

Lots of references.,,,,I'll provide all the references if you ask me….

Our first QWs….



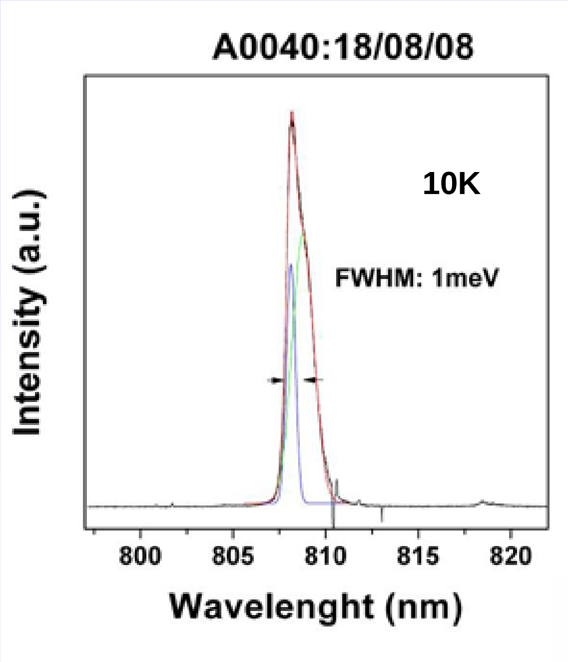
V/III ratio:

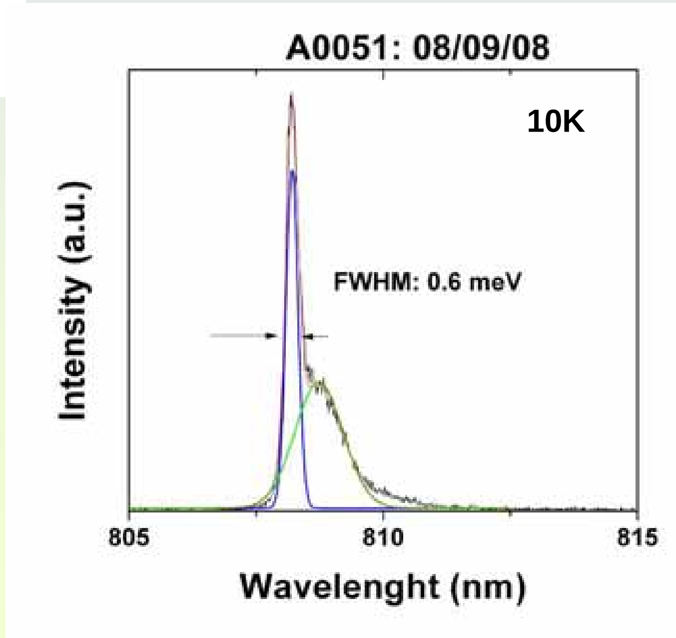
~250 for AlGaAs

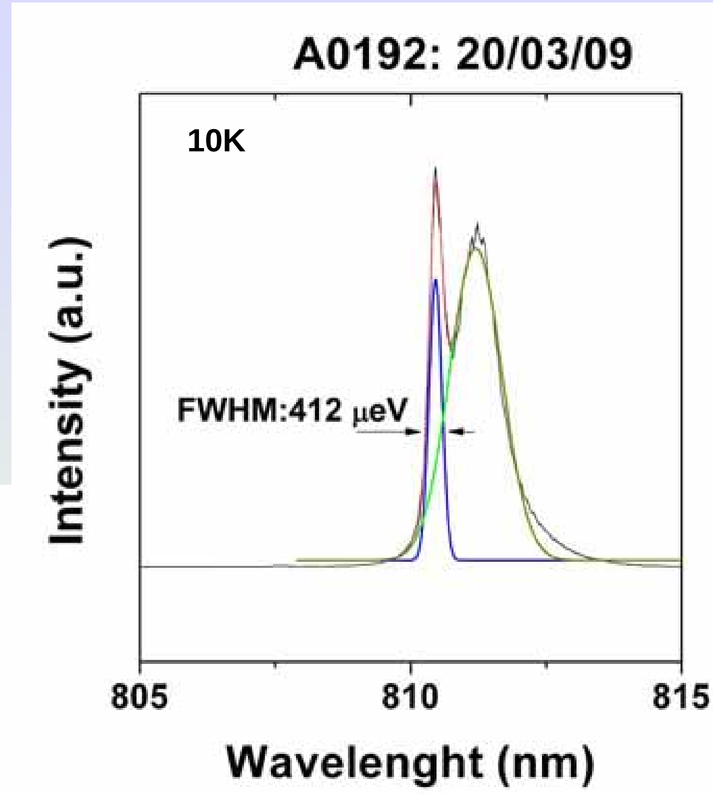
~130 for GaAs

Growth T~680C

The linewidths evolution….



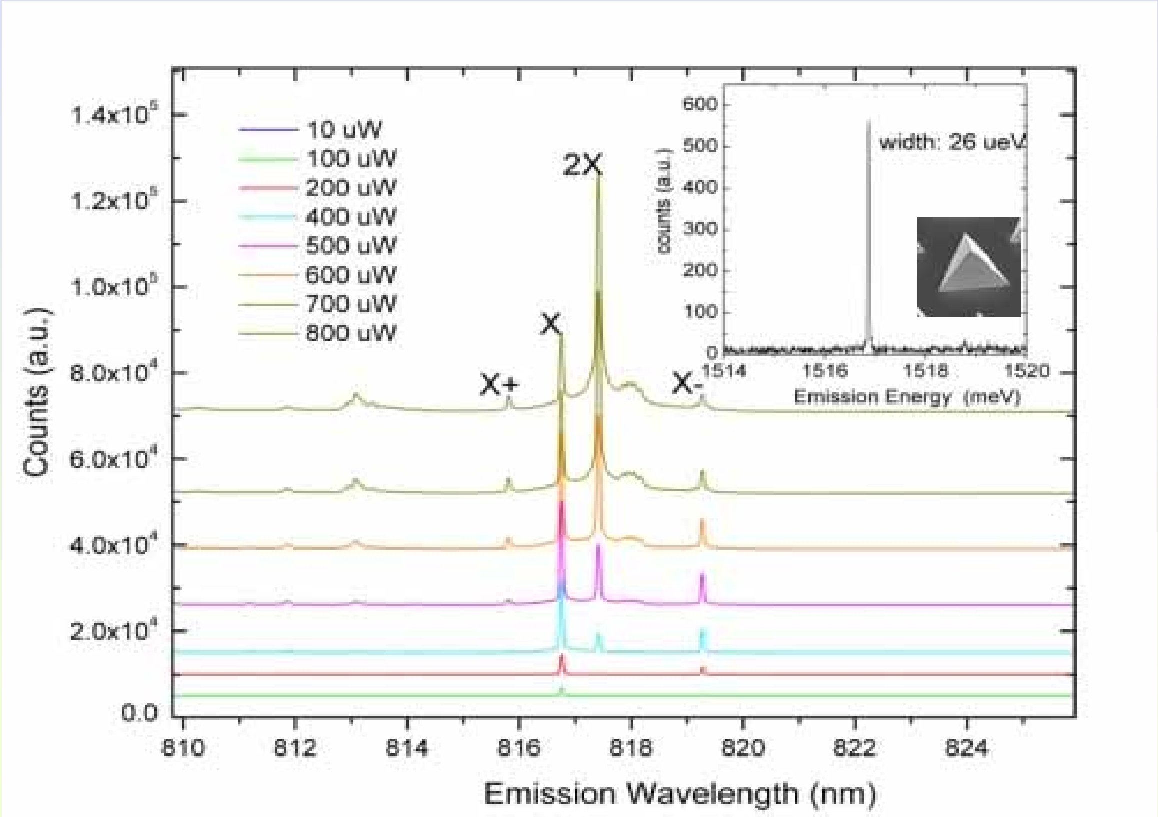




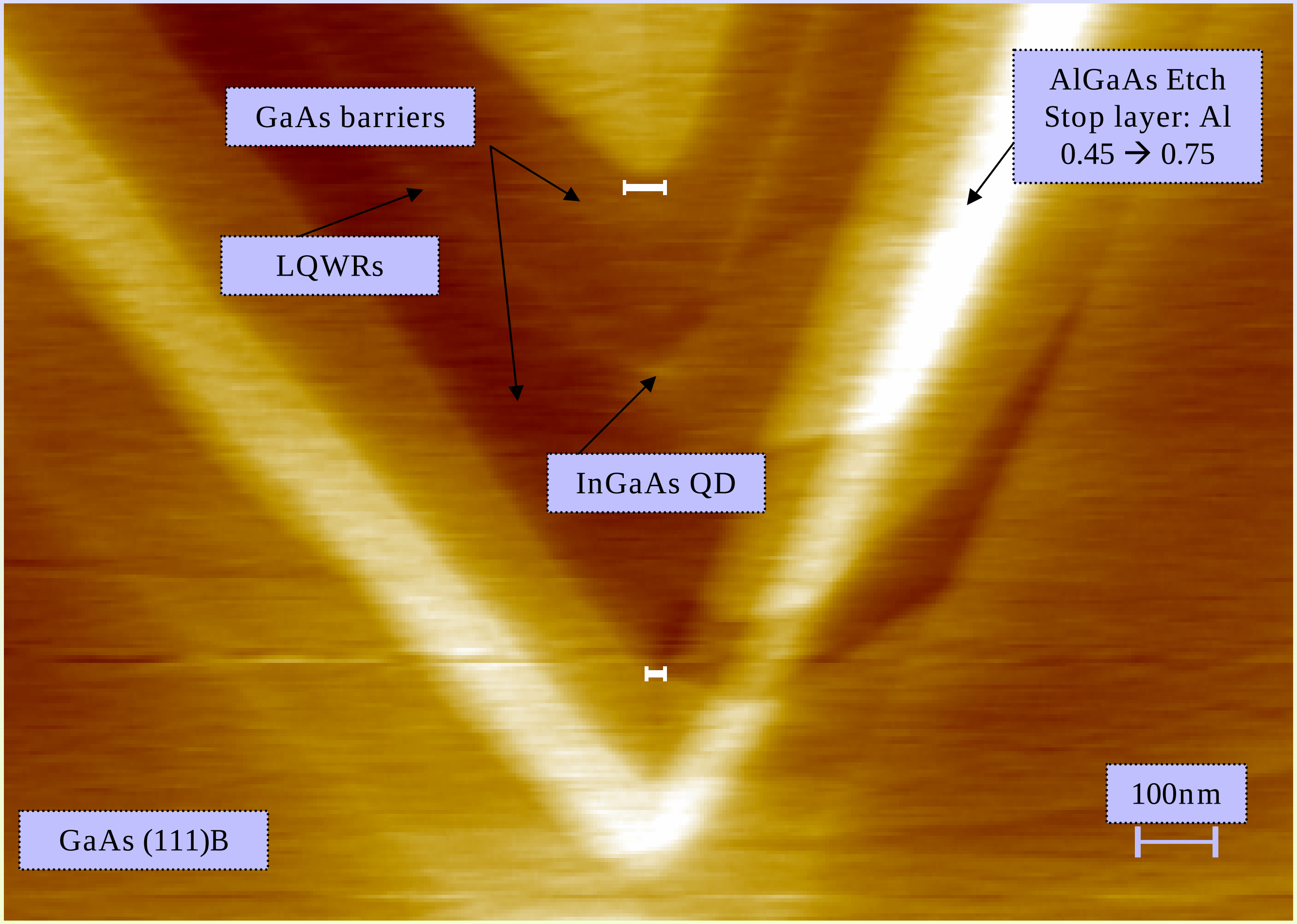
Fit with origin 8 : a disaster….

Demonstration of Pyramidal QD technology in Cork. InGaAs dots in AlGaAs barriers

Our first record linewidth for site controlled QDs…..

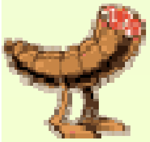


A (new) QD system. InGaAs dots in GaAs barriers…



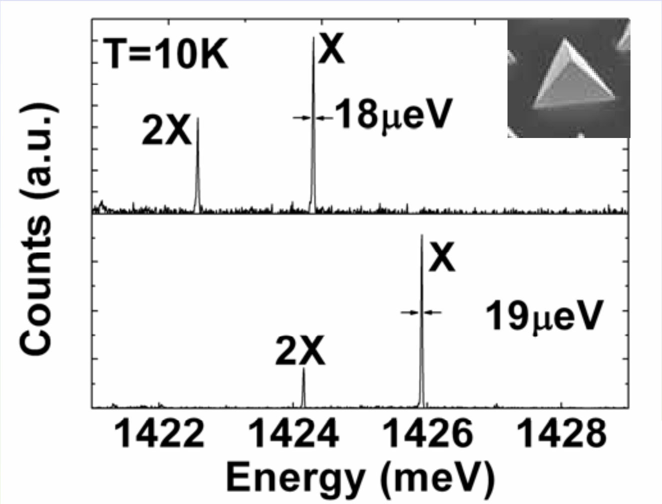
AFM cross section

1.5 nm $In_{0.25}Ga_{0.75}As$ dot in GaAs barriers

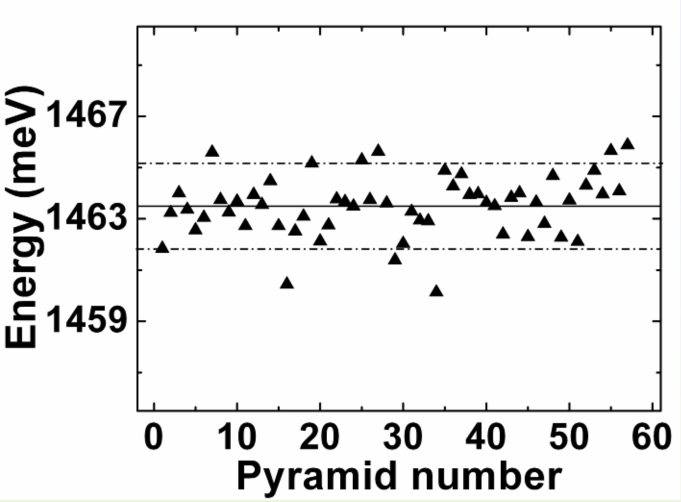


Super uniformity, and extremely narrow linewidths

Our second record linewidth



FWHM $_{(ensemble)}$=2.8 meV

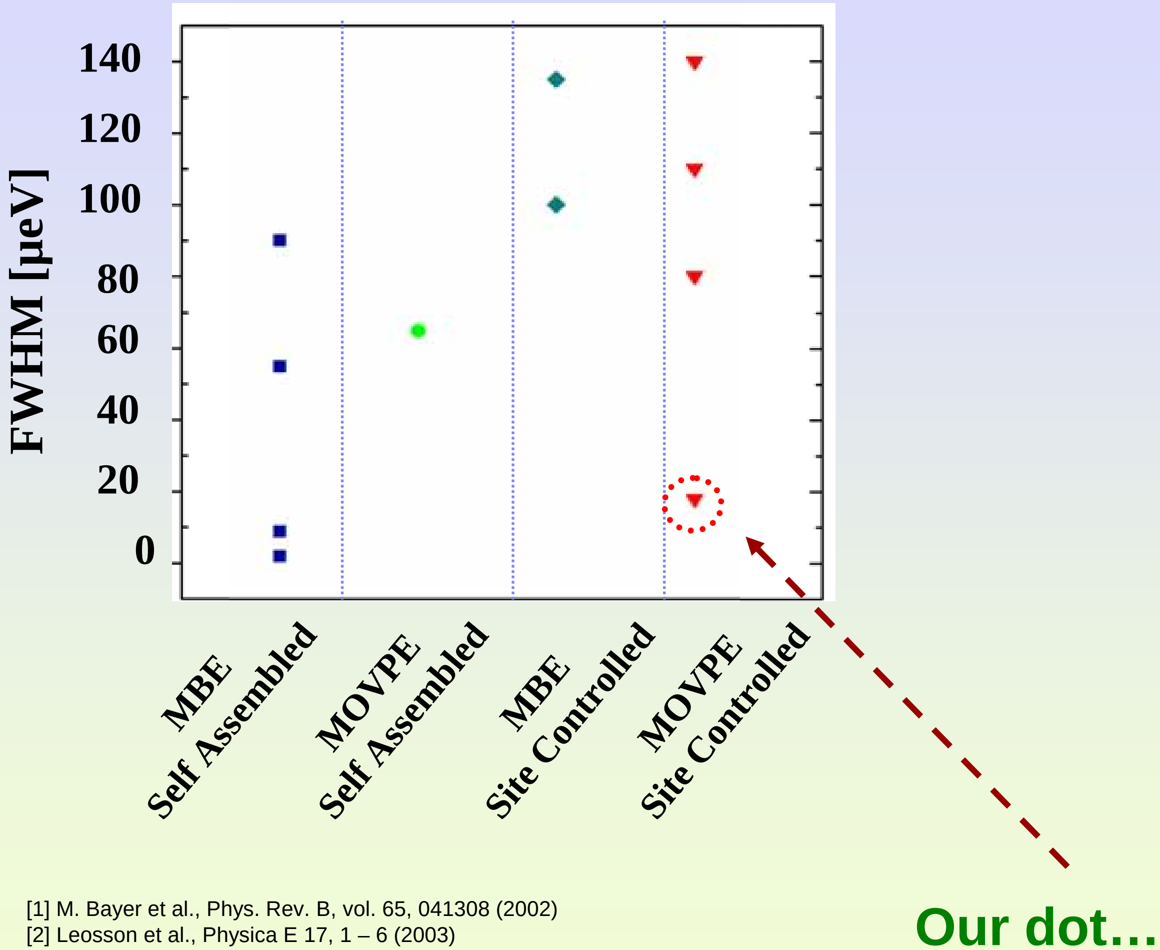


L.O. Mereni, V. Dimastrodonato, R.J. Young and E. Pelucchi, Appl. Phys. Lett. 94, 223121 (2009).

Measured as grown

0.5 nm $In_{0.25}Ga_{0.75}As$ dot in GaAs barriers

Super linewidths for site controlled QDs



No site controlled QD system with better than 80 μeV reported

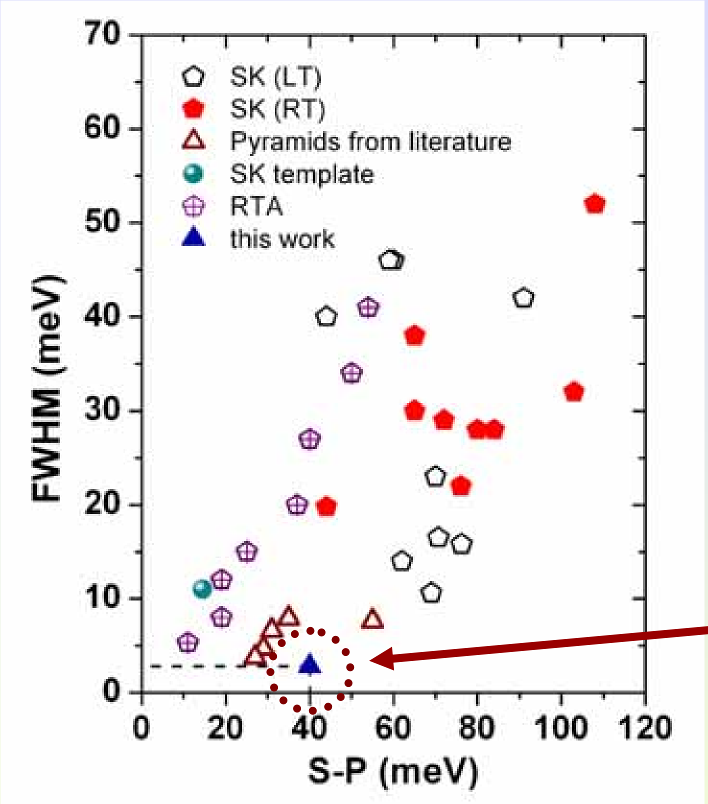
No MOVPE grown with better than 60 μeV reported

Only a few MBE grown samples show single dots with less than 10 μeV

My apology for not having updated this: one SK dots in Stuttgart I think around 30-40 μeV , and one good site controlled (~100 μeV) Wuerzburg (MBE)

[1] M. Bayer et al., Phys. Rev. B, vol. 65, 041308 (2002)
[2] Leosson et al., Physica E 17, 1 – 6 (2003)
[3] A.J. Shields et al., Phys. Stat. Sol. (b) 238, No. 2, 353– 359 (2003)
[4] D. Xiu-Ming et al., Chin. Phys. Lett. Vol. 25, No. 2 (2008) 501
[5] R. M. Stevenson et al., Appl. Phys. Lett., Vol. 87, 233102 (2006)
[6] S.Kiravittaya et al., Appl. Phys. Lett., Vol. 89, 233102 (2006)
[7] Tung-Po Hsieh et al., Nanotechnology 17, 512–515 (2006)
[8] L. O. Mereni et al., Appl. Phys. Lett., to be published
[9] D.Y. Oberli et al., unpublished
[10] H. Chang et al., Phys. Stat. Sol. (c) 5, No. 9, 2713–2715 715 (2008)
[11] E.Kapon et al., Physica E, 25, 288-297 (2004)

World leading uniformity while preserving substantial confinement



S-P: fundamental to first excited state/barrier level separation

Selection of literature data on the FWHM of luminescence spectra versus the S-P transitions energy separation for SK and pyramidal QDs. SK(LT): low temperature luminescence data for SK dots [Ref. 1, 2]; SK(RT): room temperature luminescence data for SK dots [Ref.3]; Pyramids from literature: low temperature PL and cathodoluminescence data for pyramidal QDs [Ref. 4]; SK template: low temperature PL data for GaAs QDs grown inside etched SK dot template [Ref. 5]; RTA: low temperature PL data for SK dots after rapid thermal annealing [Ref. 2]; this work: our best sample.

Our dot…and have to add Lausanne's results..

[1] E. C. Le Ru,et al, Phys. Rev. B 67, (2003) 165303; Tao Yang et al., Appl. Phys. Lett. 84, (2004) 2817; V. Celibert, et al., J. Cryst. Growth 275, (2005) e2313; Zetian Mi and Pallab Bhattacharya, J. Appl. Phys. 98, (2005) 023510; B. Alloing, et al., Appl. Phys. Lett. 86, (2005) 101908.

[2] S. Fafard and C. Nì. Allen, Appl. Phys. Lett. 75, (1999) 2374; N. Perret, et al., Phys. Rev. B 62, (2000) 5092; J. J. Dubowski, et al., Appl. Phys. Lett. 77, (2000) 3583.

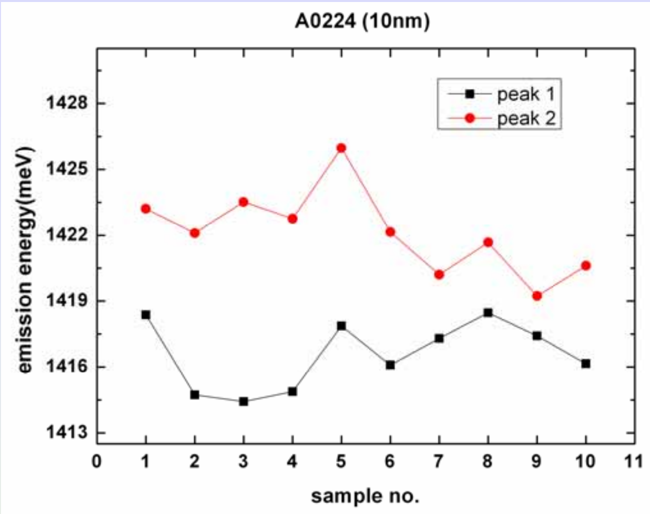
[3] Jun Tatebayashi, et al., Appl. Phys. Lett. 78, (2001) 3469; Z. Y. Zhang, et al., J. Appl. Phys. 92, (2002) 511; Y. Q. Wei, et al. Appl. Phys. Lett. 81, (2002) 1621; B. Alloing and A. Fiore et al., private communication.

[4] M. H. Baier, et al., Appl. Phys. Lett. 84, (2004) 11; S. Watanabe, et al., Appl. Phys. Lett. 84, (2004) 2907; K. Leifer, et al., Appl. Phys. Lett. 91, (2007) 81106.

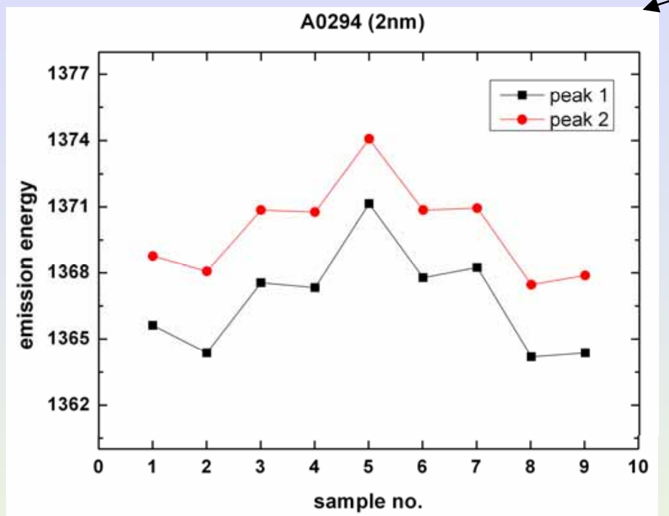
[5] A. Rastelli, et al., Phys. Rev. Lett. 92, (2004) 166104.

QD molecule formation…

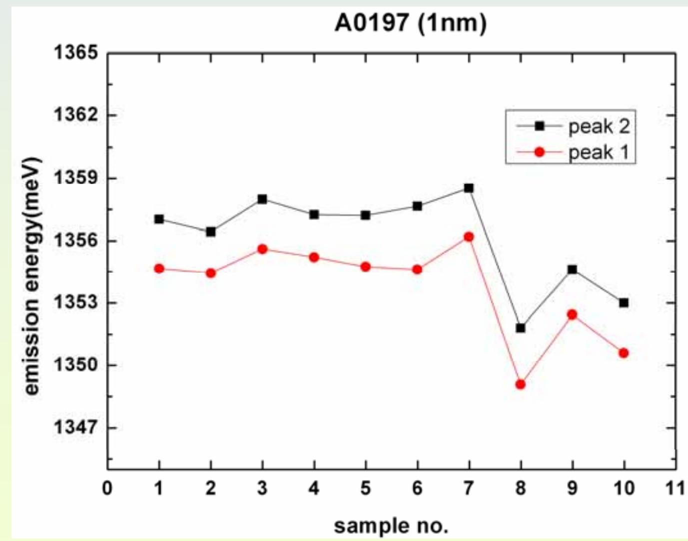
Two thin QDs….0.5 nm, 25% In

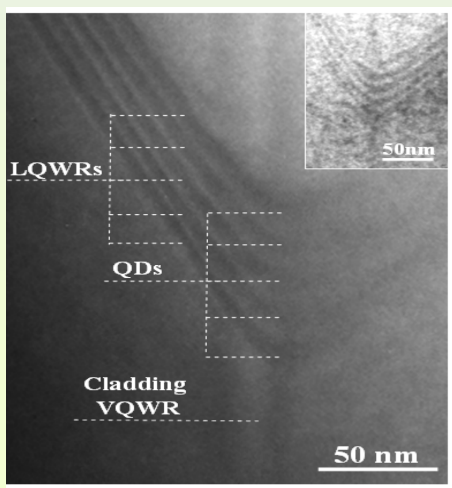


Uncorrelated when barrier is 10 nm



Fully correlated and red shifted when barrier is small





Only the figure: Q. Zhu et al, Small 2009, 5, No. 3, 329–335

Next steps :

-broadening the materials used…

-improving dot coupling and theoretical simulation

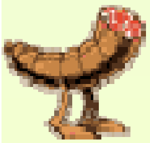
-electrical control

-even better PL properties

-dots in cavities

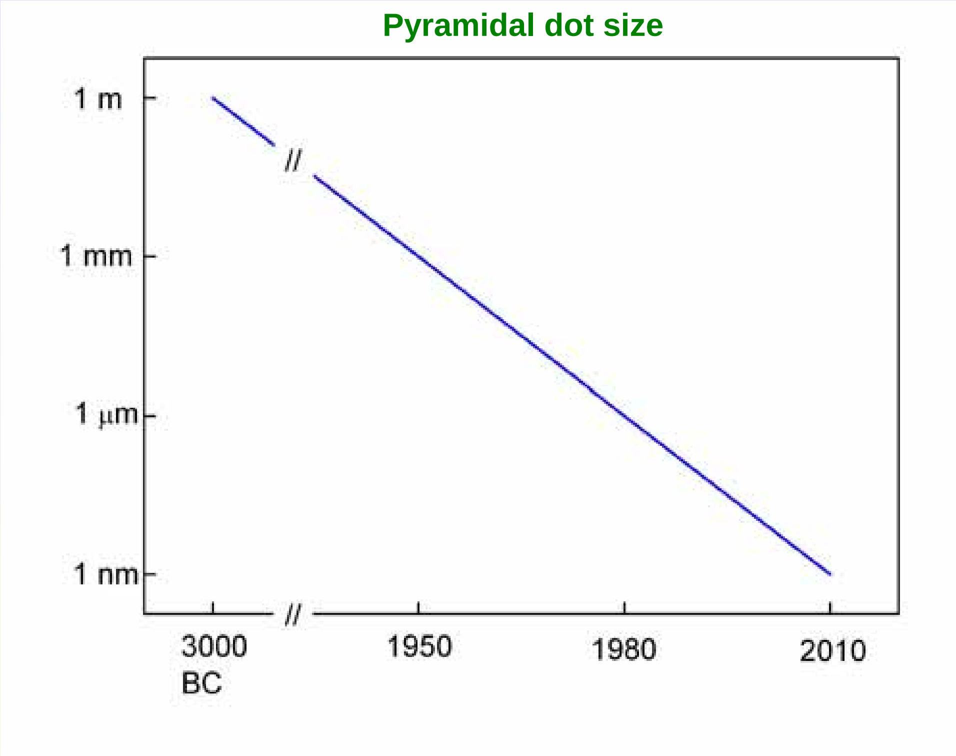
-……

The ideal dot



Technology challenges: Moore's law

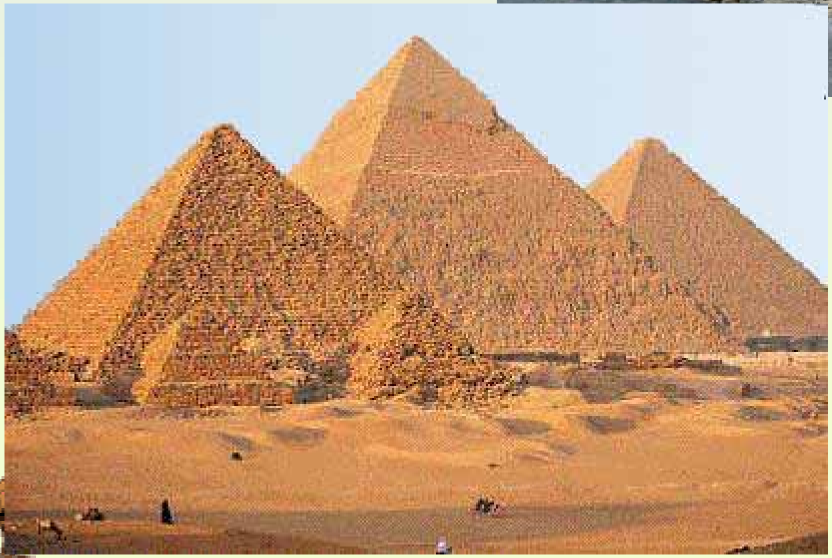
Historical Highlight



Now we work with nanometer dots……device/dot size was much bigger in the past….

Early Pyramidal quantum dots….Ireland was obviously well ahead of Egypt in the rush towards miniaturization…

Historical Highlight

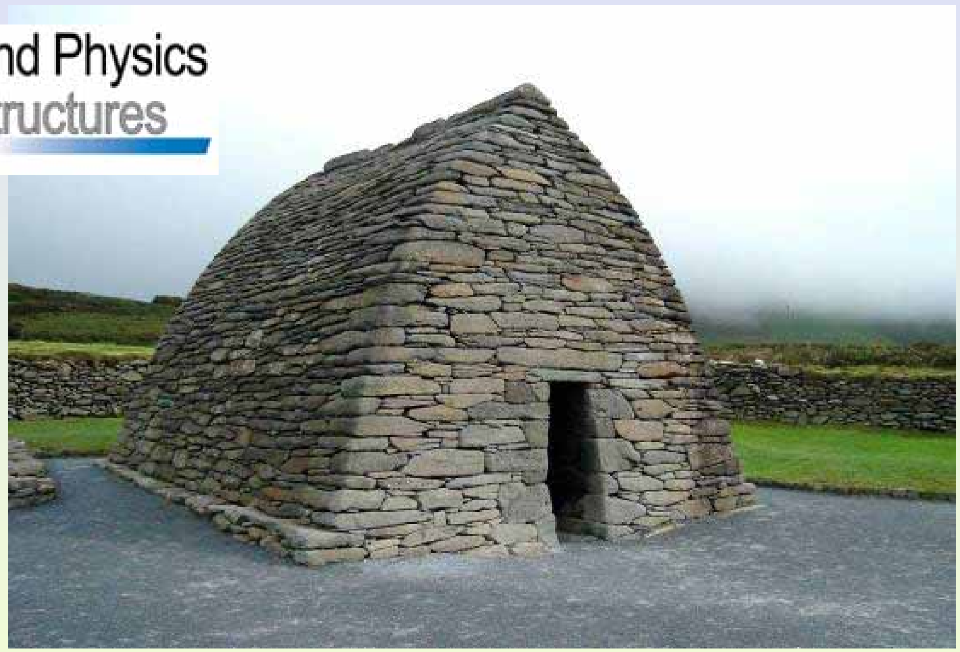


Thanks

Tyndall National Institute

science foundation ireland
fondúireacht eolaíochta éireann

Epitaxy and Physics of Nanostructures



~Ring of Kerry

NDP
National Development Plan 2007 - 2013

HEA
Higher Education Authority
An tÚdarás um Ard-Oideachas

UCC
Coláiste na hOllscoile Corcaigh, Éire
University College Cork, Ireland