

Selective area epitaxy (II) : non-planar growth

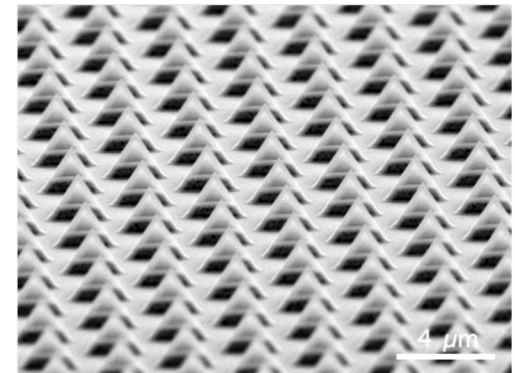
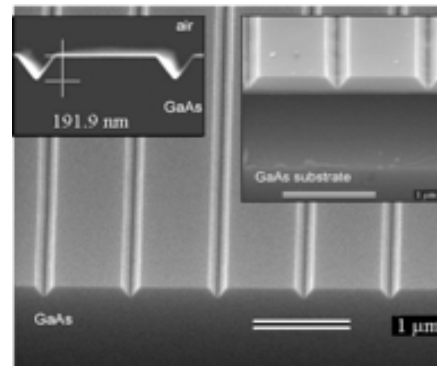
Spatial modulation of surface kinetics:

- Partly cover surface with a *mask* material which has a different chemical reactivity to the growth precursors compared to the original substrate
- • Modulate cristallographic orientation by *non-planar* patterning
- Build spatially localised *strain fields* below the growth surface that will modify the surface growth kinetics

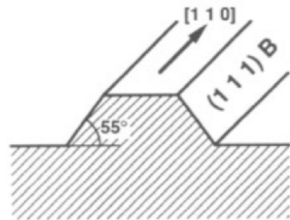
→ Patterned growth



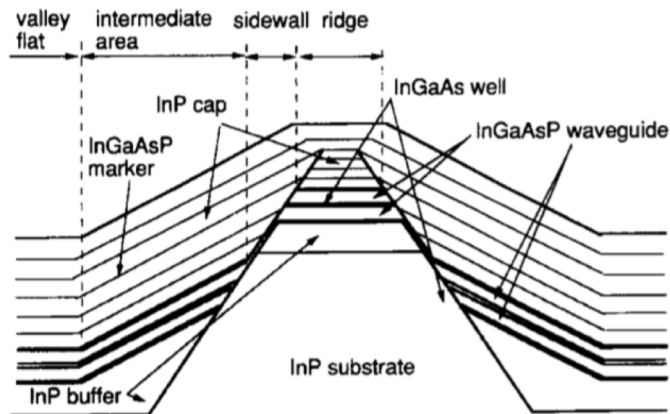
Precursors (P)



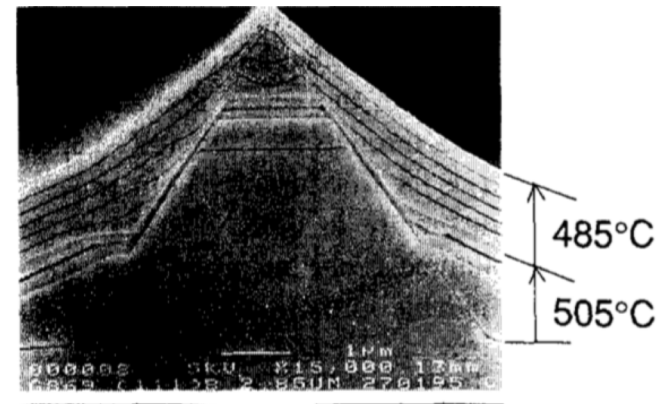
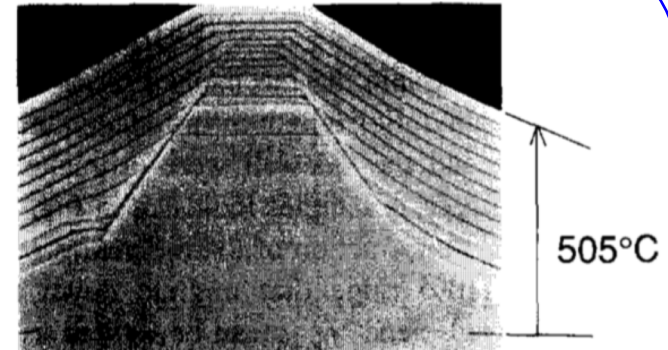
Chemical Beam Epitaxy on non-planar InP substrates



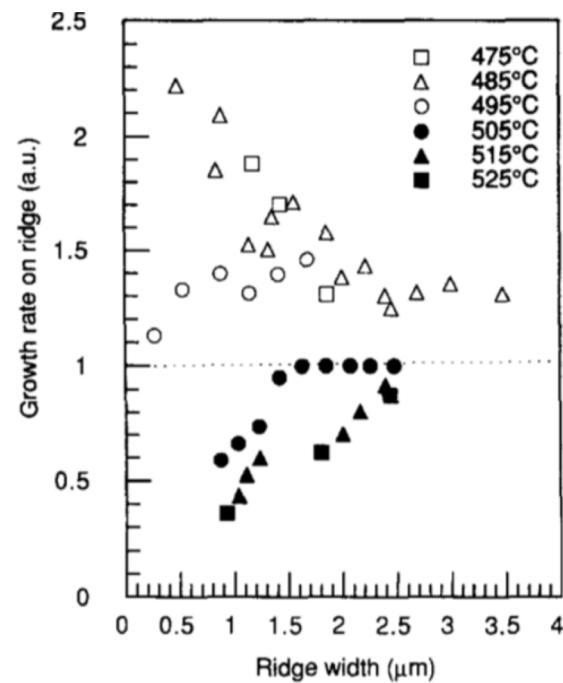
- TEGa, TMIn, AsH₃, PH₃
- T: 475 - 525° C
- InP (100) patterned with ridges along 110
- InP buffer
- InGaAsP waveguide with InGaAs QW
- InP cap with InGaAsP marker layers



➤ InP & InGaAs do not grow on InP (111)B

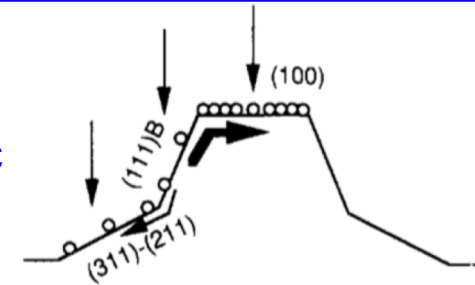


Temperature dependence of interfacet migration

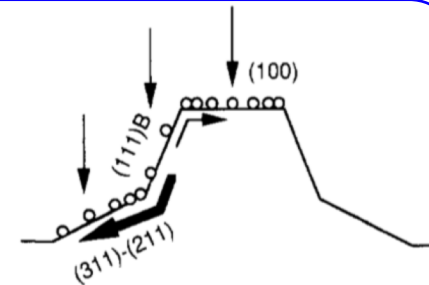


InP ridge growth rate vs ridge width

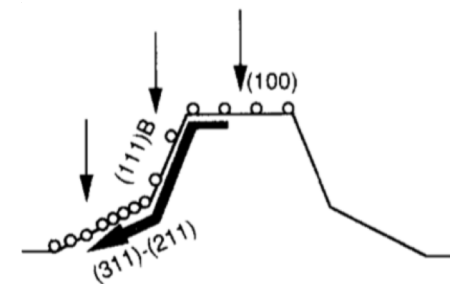
$T < 485^\circ \text{C}$



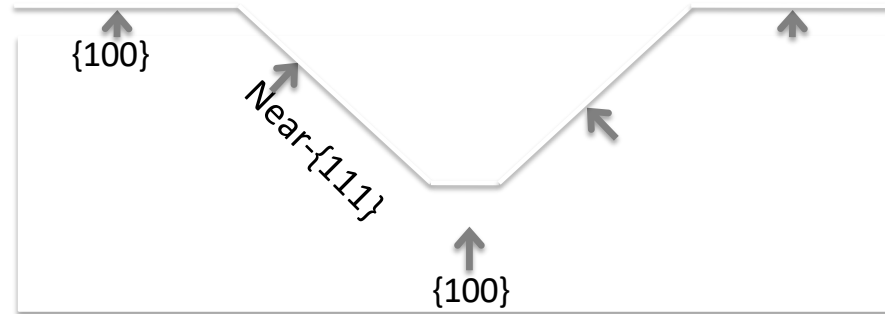
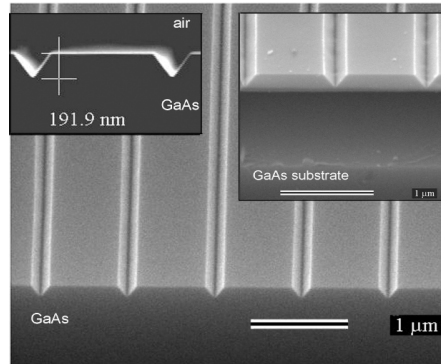
$T = 495^\circ \text{C}$



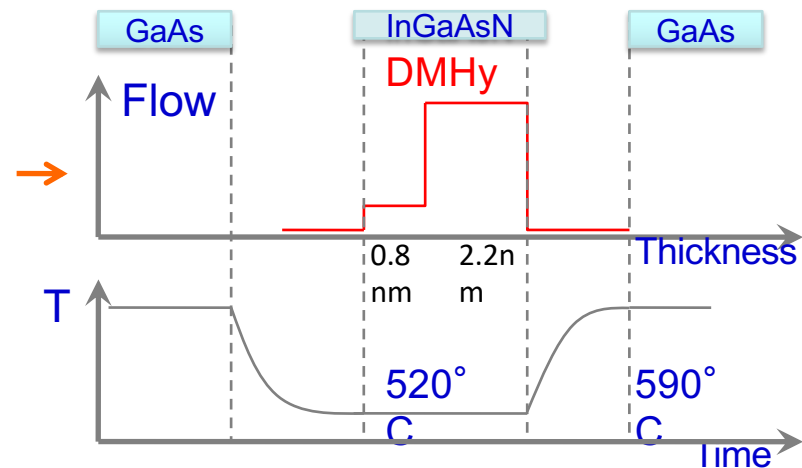
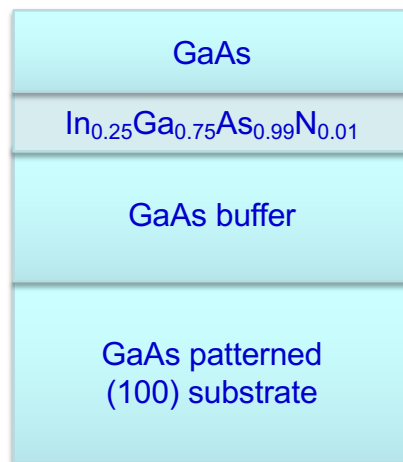
$T > 505^\circ \text{C}$



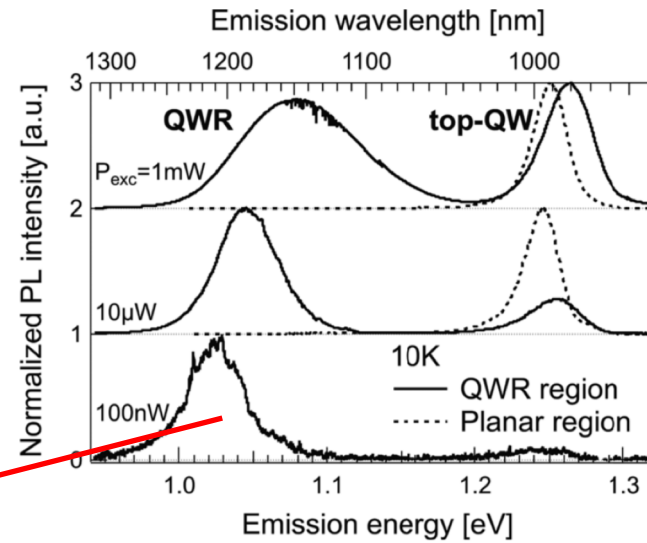
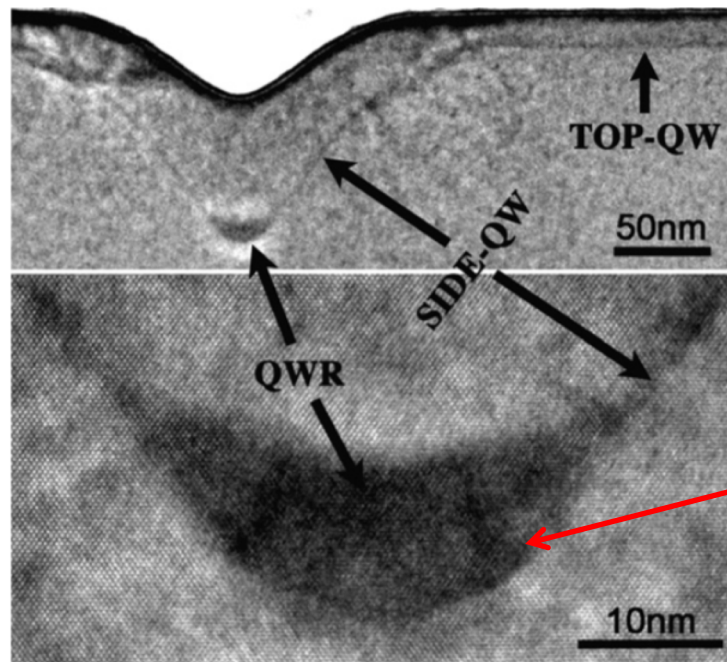
Growth of GaInAsN/GaAs on V-grooved surfaces



- Chemical potential variation (capillarity)
- More important growth at the bottom
- → Self-limited profile



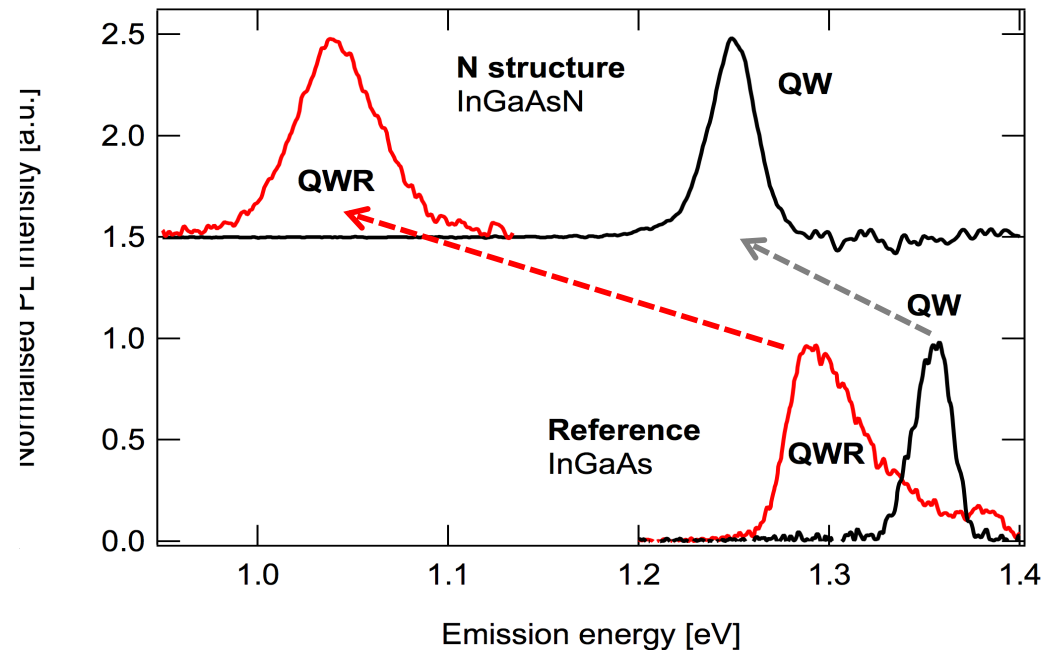
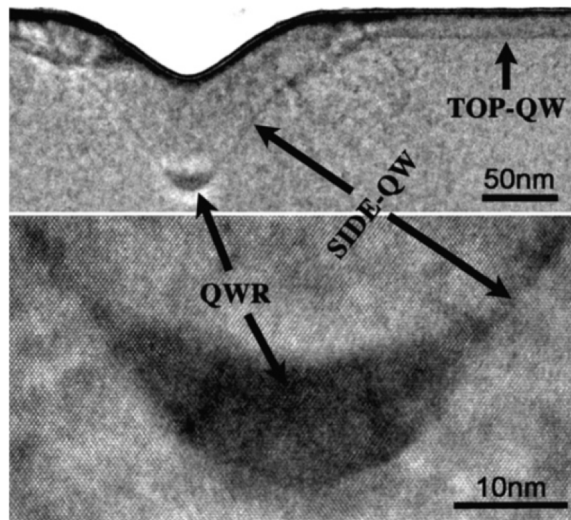
GaInAsN/GaAs quantum wires



10K PL spectra of an InGaAsN/GaAs QWR

TEM cross-section of the QWR structure

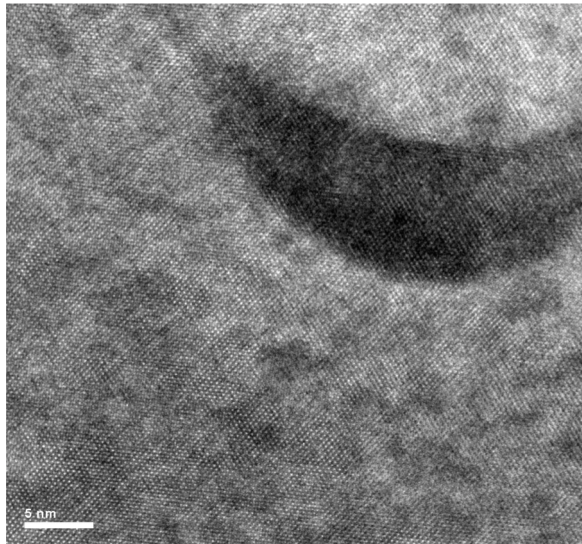
N incorporation in QWs and QWRs



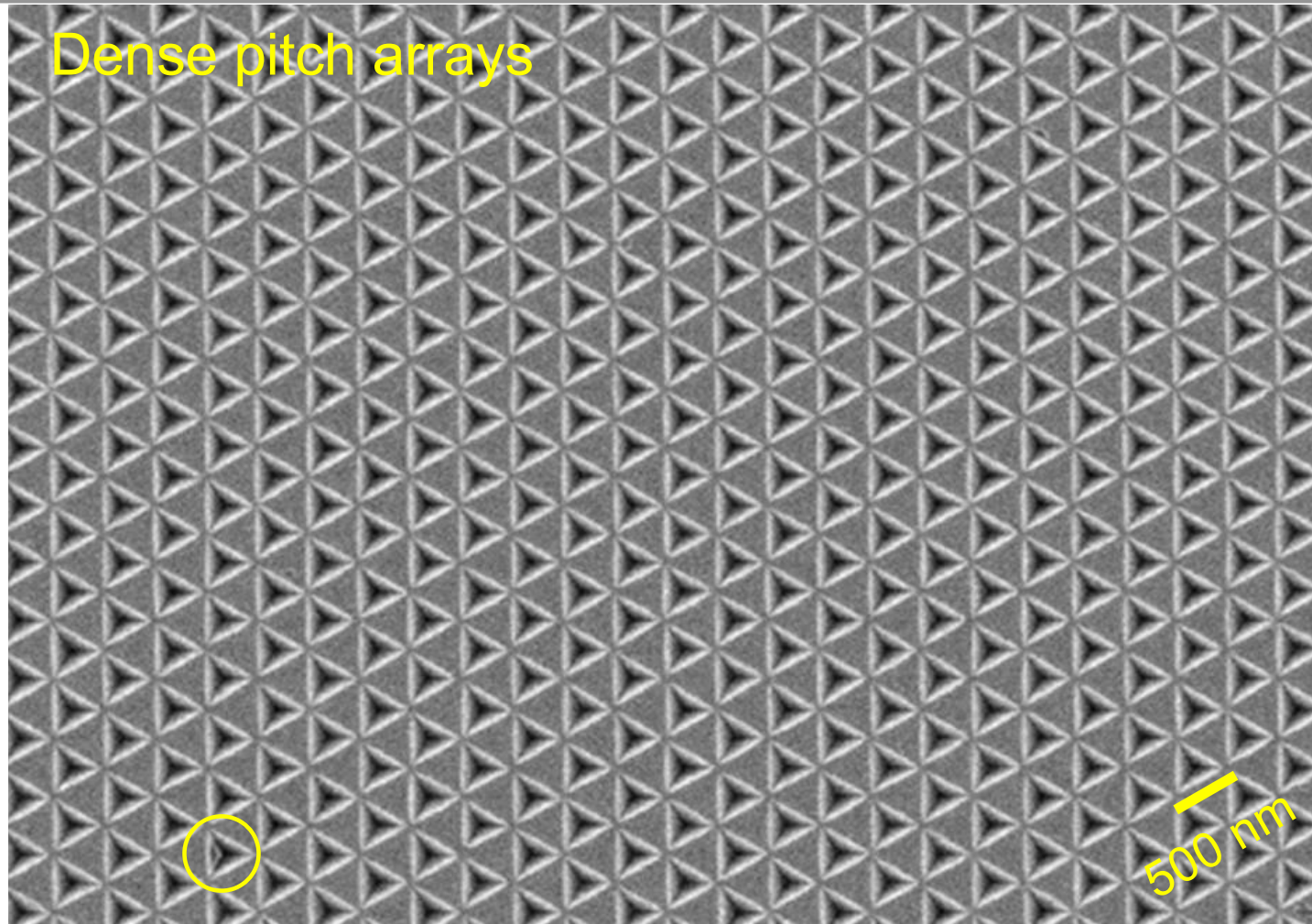
- Higher growth rate for the QWR
- Decrease of N desorption from the surface
- Larger energy shift for the QWRs

Summary - InGaAsN QWs & QWrs

- Enhanced N uptake on vicinal (100) substrates
- Enhanced N incorporation on non-planar substrates
- V-groove QWRs emitting at $1.3\mu\text{m}$ at room temperature

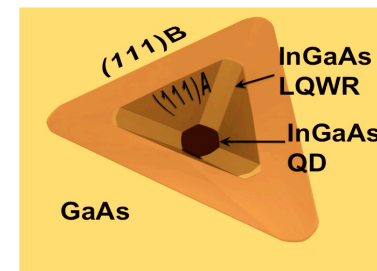
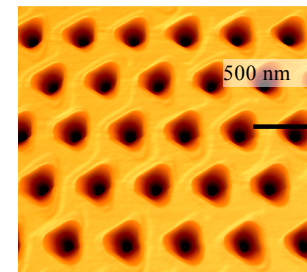
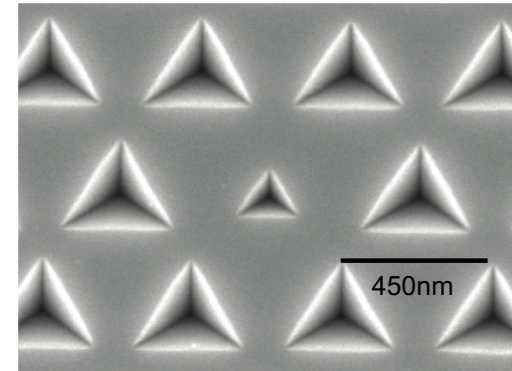


Non-planar epitaxy on 2D patterns



Multiwavelength InGaAs quantum dot arrays

- Motivations & challenges
- MOVPE of “pyramidal” Quantum Dots
- Spectral & spatial control of QDs
- Spectral & spatial isolation of QDs
- Summary



NANOPHOTONICS

Electron + photon confinement >> integrated nano-photonics

Demands for improved data:

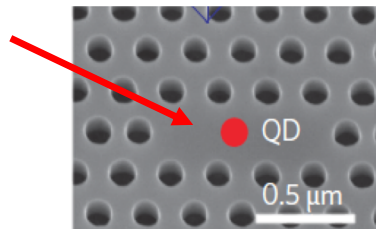
- Storage
- Transmission
- Treatment

Quantum devices

- Single-photon emitters
- Quantum-entangled photon sources
- Low-current and high-speed lasers
- Integrated photonic devices

Quantum logic gate

InAs QD
coupled
To photonic
crystal
cavity



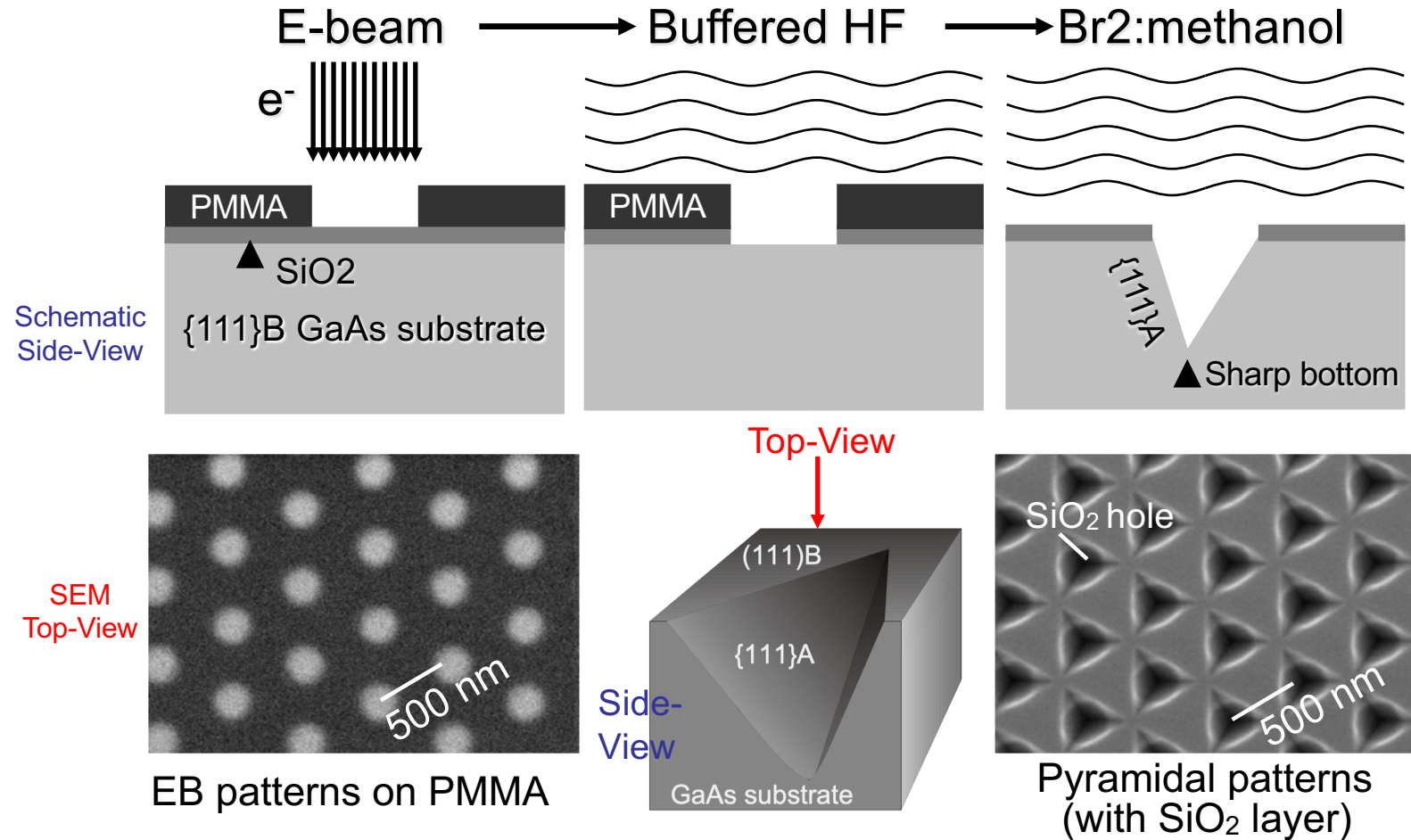
Kim *et al.*, Nature Photonics (2013)

Stranski-Krastanov QDs

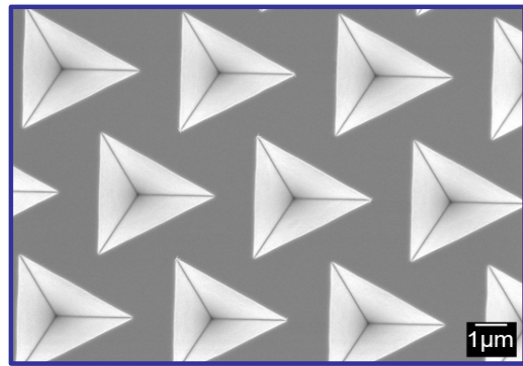
SK dots nucleate randomly:

- “Soft” site control not accurate enough
- “Hard” site control damages the QDs

Substrate Preparation: e-beam lithography + selective wet etching



MOVPE of pyramidal quantum dots: localized growth controlled by substrate patterning

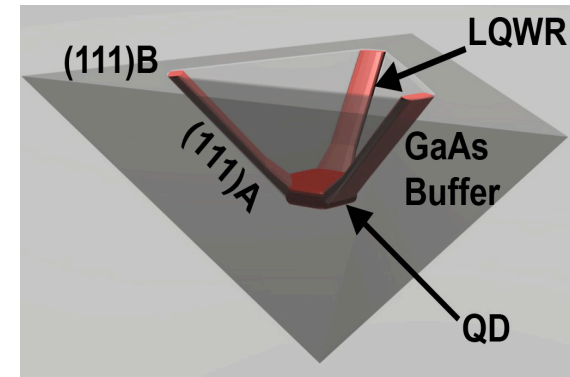


Patterned GaAs substrate
(Top View SEM)

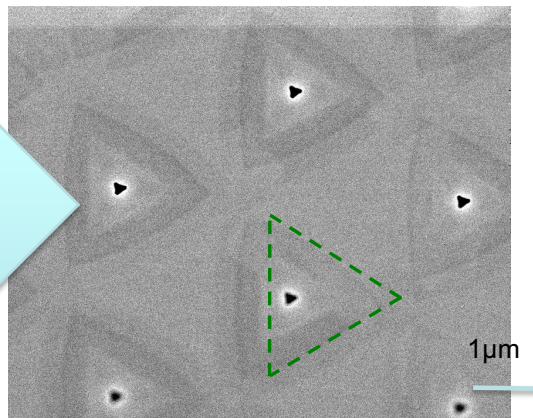
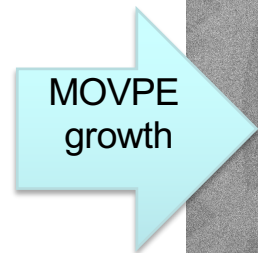
(111)B, As-terminated :
quasi inert

(111)A : Ga-terminated:
Adatom incorporation

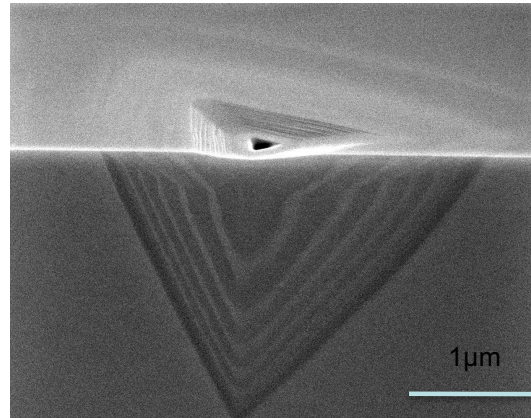
- Adatom migration
- Capillarity



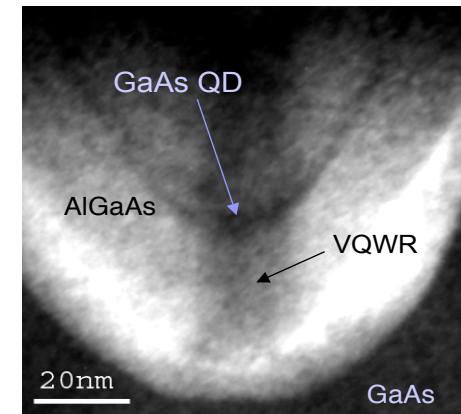
E. Kapon *et al.*, APL 50, 347 (1987)
G. Biasiol *et al.*, PRL 81, 2962 (1998)



SEM Top View

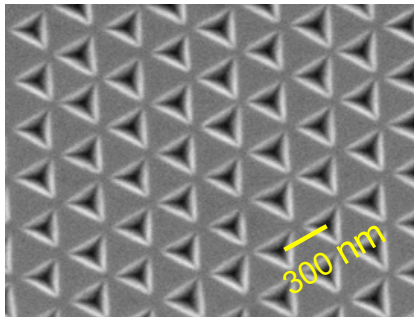


SEM cross-section



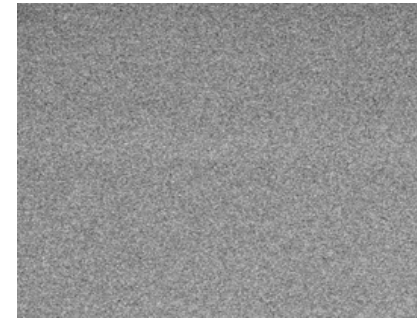
TEM Cross Section

GROWTH PARAMETERS

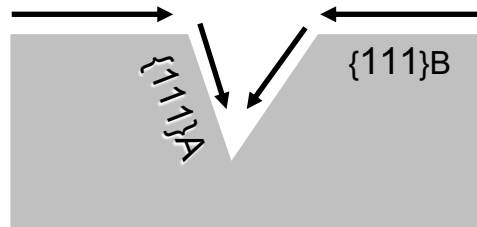


Original substrate

Deoxidize under AsH_3
at 730°C

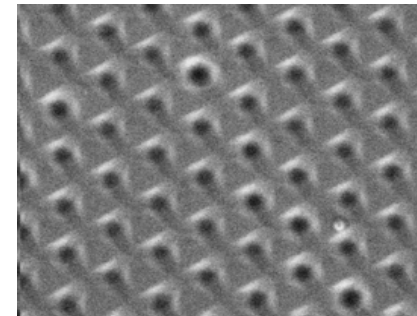


Surface mass transport

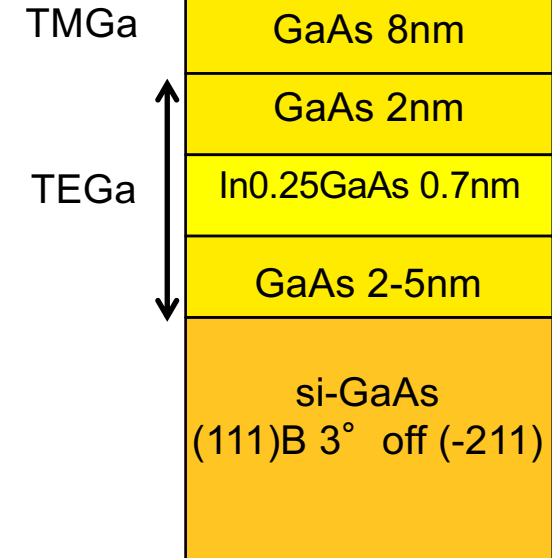
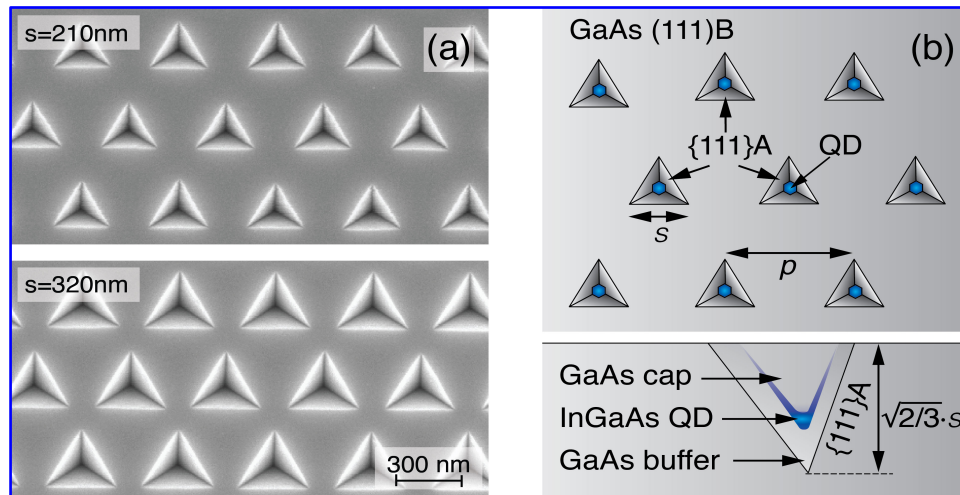


- Deoxidation under AsH_3 : 4mn @ 600°C
- si-GaAs (111)B + 3° towards (-211)
- 20mbars, $550\text{--}600^\circ\text{C}$, N_2 ambient (total flow 7l/mn)
- TEGa, TMGa, TMIn, TEIn, AsH_3
- 0.01nm/s on (100)

At $\sim 620^\circ\text{C}$



MOVPE OVER SETS OF UNIFORM ARRAYS OF PYRAMIDS



Varying pyramidal size s at constant pitch p

affects

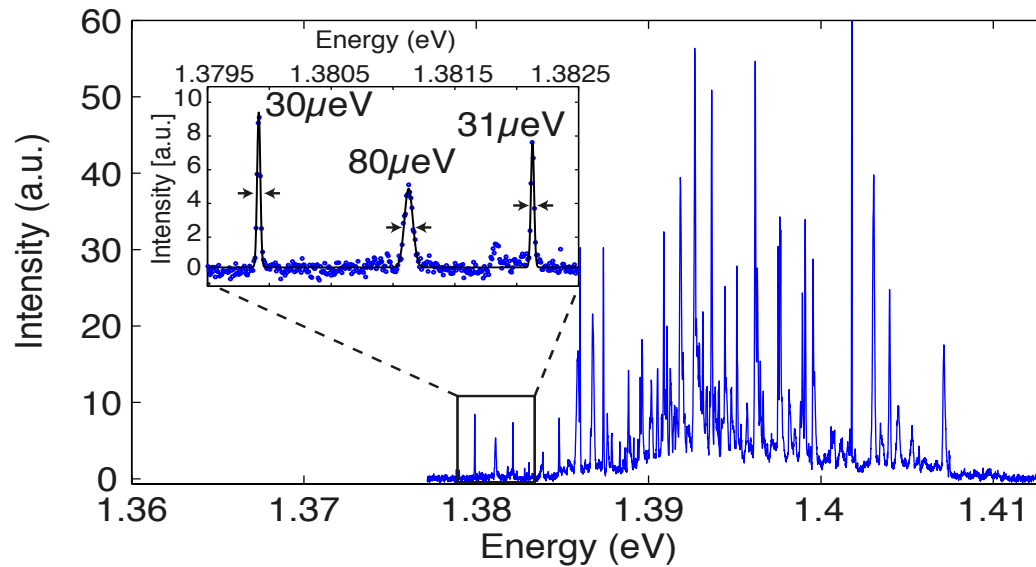
- Metalorganic decomposition
- Admolecule population

*Modifies
the QD*

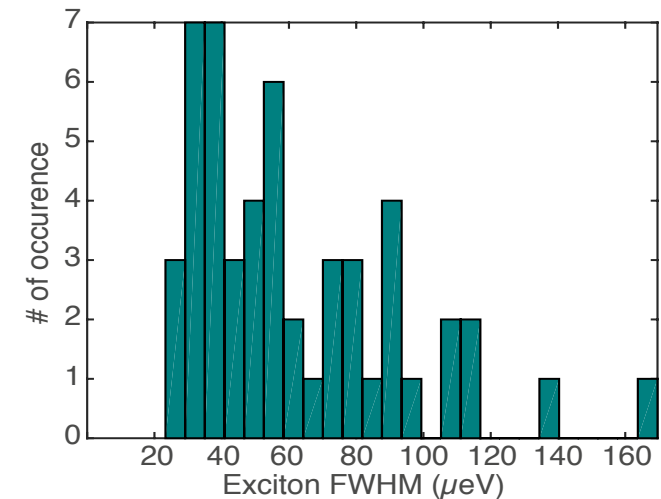
- Growth rate
- Thickness and In %
- Emission energy

Site-controlled QDs with narrow PL emission

Micro-PL of an ensemble of
30-40 QDs

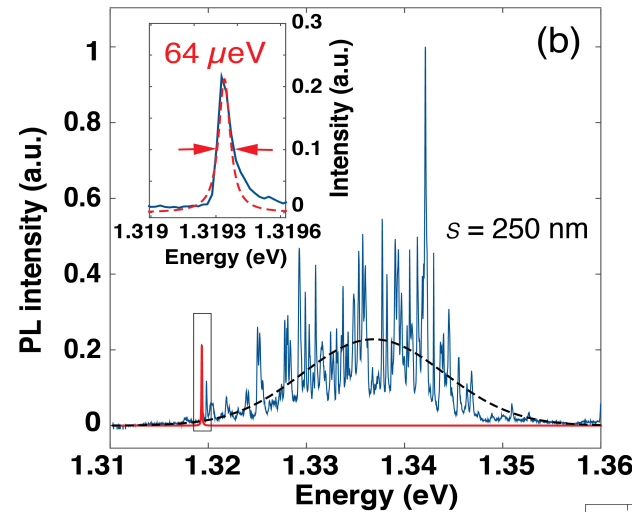
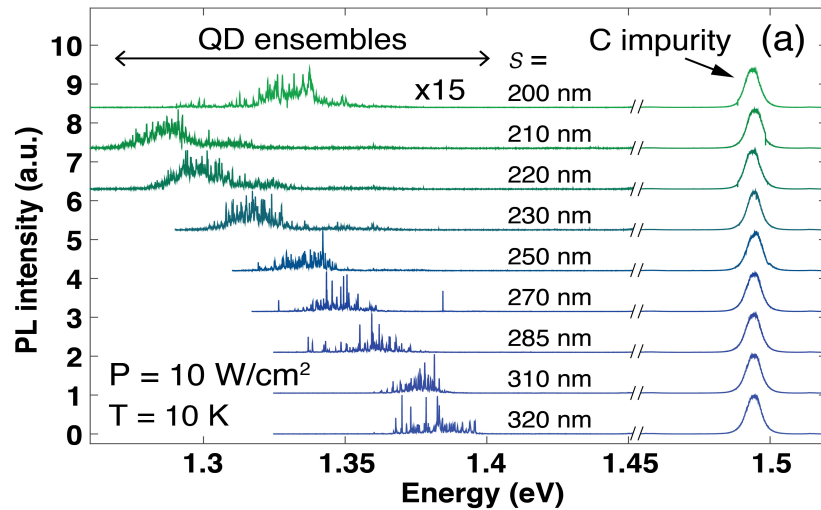


InGaAs QDs excitonic
linewidth < 30 μeV



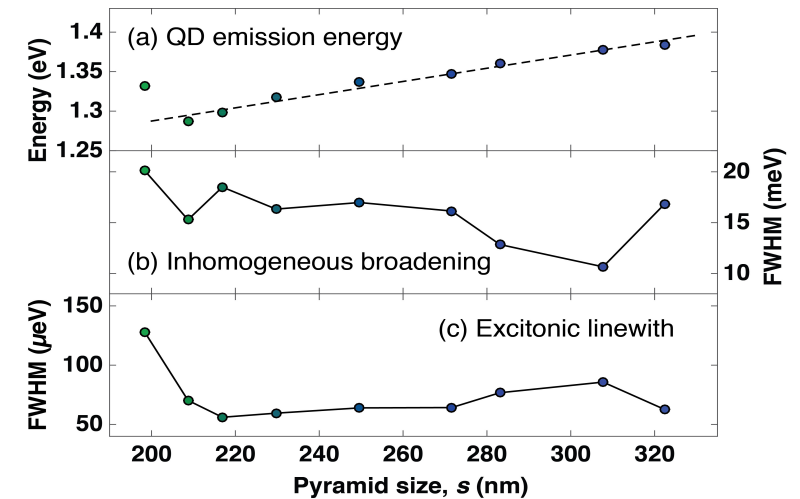
PL resolution limit 25 μeV

Controlling QD energy through pyramid size

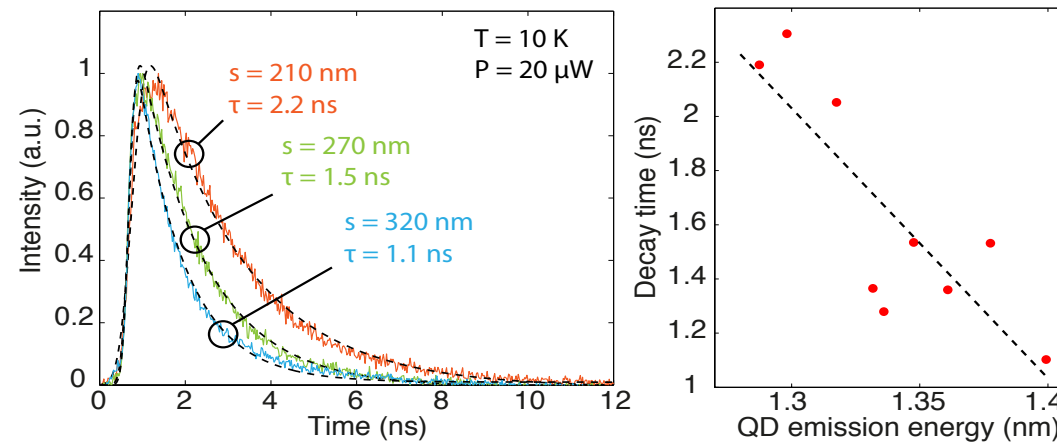


With larger pyramid size:

Higher QD emission energy
Lower inhomogeneous broadening
Comparable excitonic linewidth

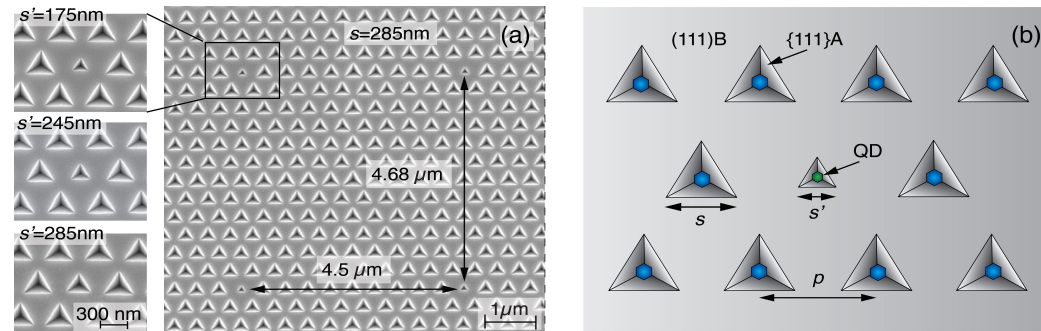


Time resolved photoluminescence on QD ensembles

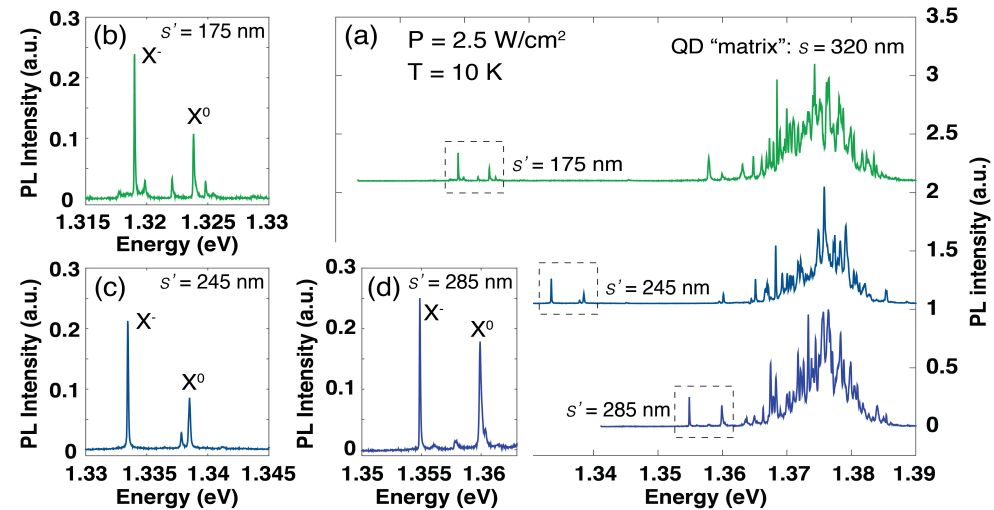


- Average decay time τ : 1 - 2.3 ns
- τ decreases with increasing QD emission energy
- Smaller QDs > larger electron-hole wave function overlap

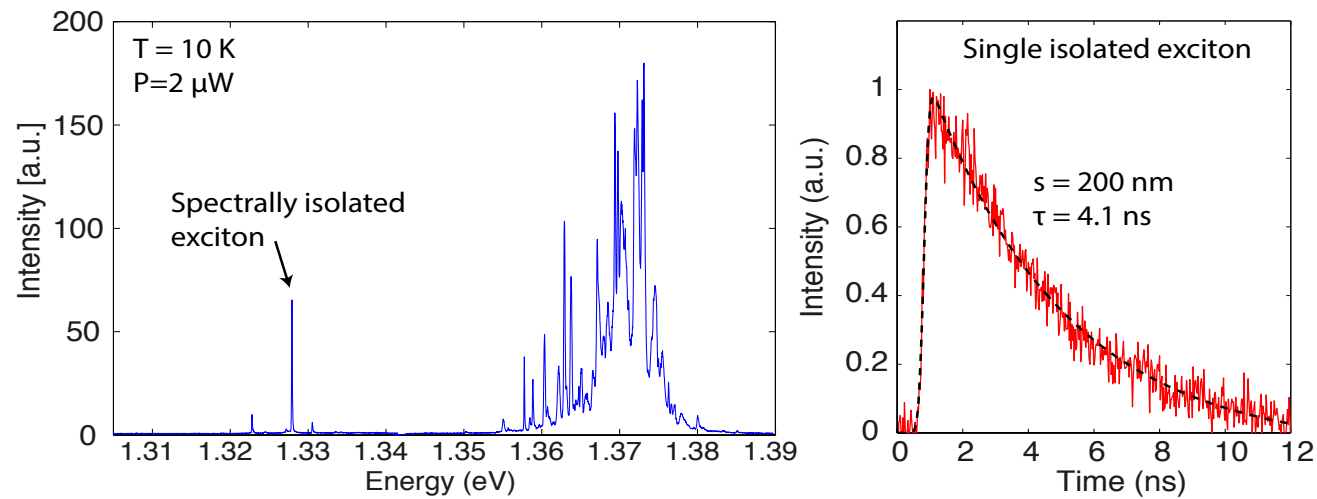
Isolating QDs through pyramid size



Uniform matrix ($s=320\text{nm}$)
Isolated smaller QDs
Single QD spectroscopy
No processing needed

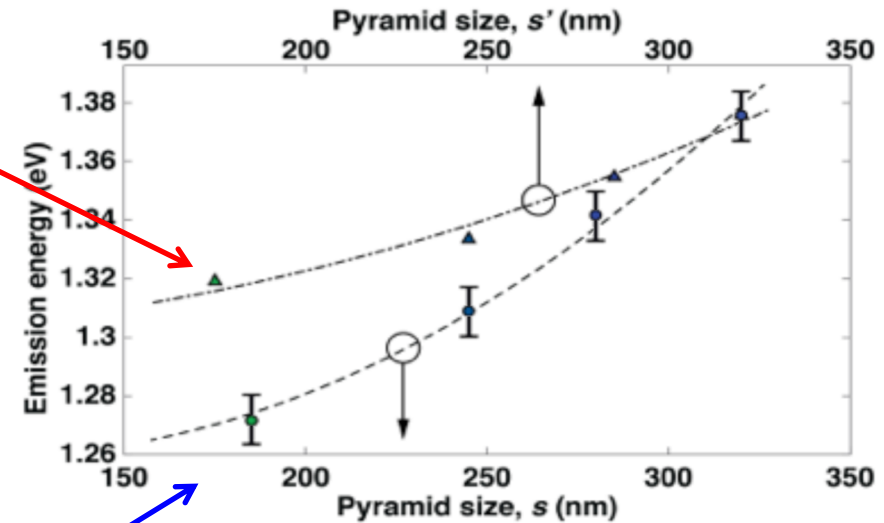
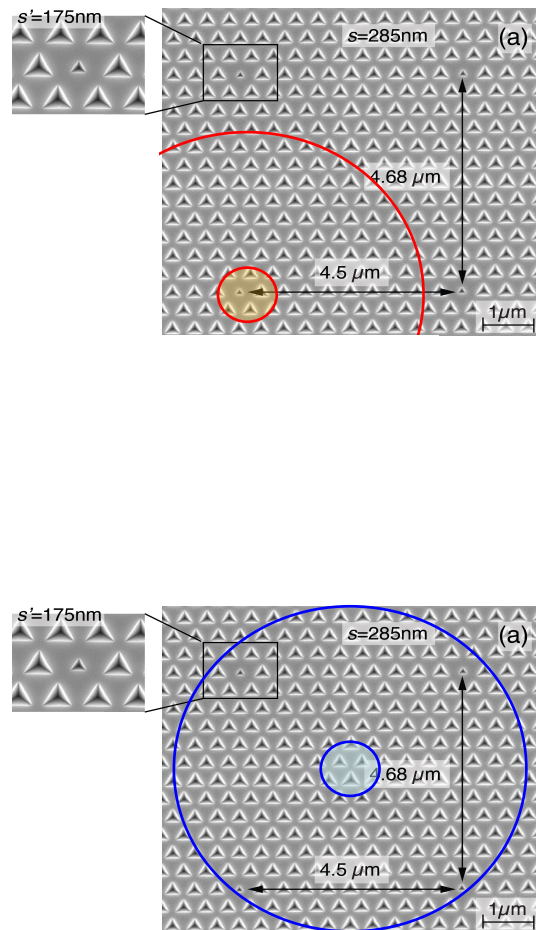


Time resolved photoluminescence on single QD



- PL decay measured on single spectrally isolated QD
- Valuable tool for cavity design

Controlling isolated QD emission energy through pyramid size



QD energy increases with pyramid size:
Strong dependence in homogeneous array (100meV)
Weaker dependence in isolated QDs (40 meV)
QD energy span sufficiently large for WDM source

Ethyl- vs methyl- precursors: intrinsic C uptake

Inst. Phys. Conf. Ser. No. 63 : Chapter 3

Paper presented at Int. Symp. GaAs and Related Compounds, Japan, 1981

Acceptor incorporation in high-purity OMCVD grown GaAs using trimethyl and triethyl gallium sources

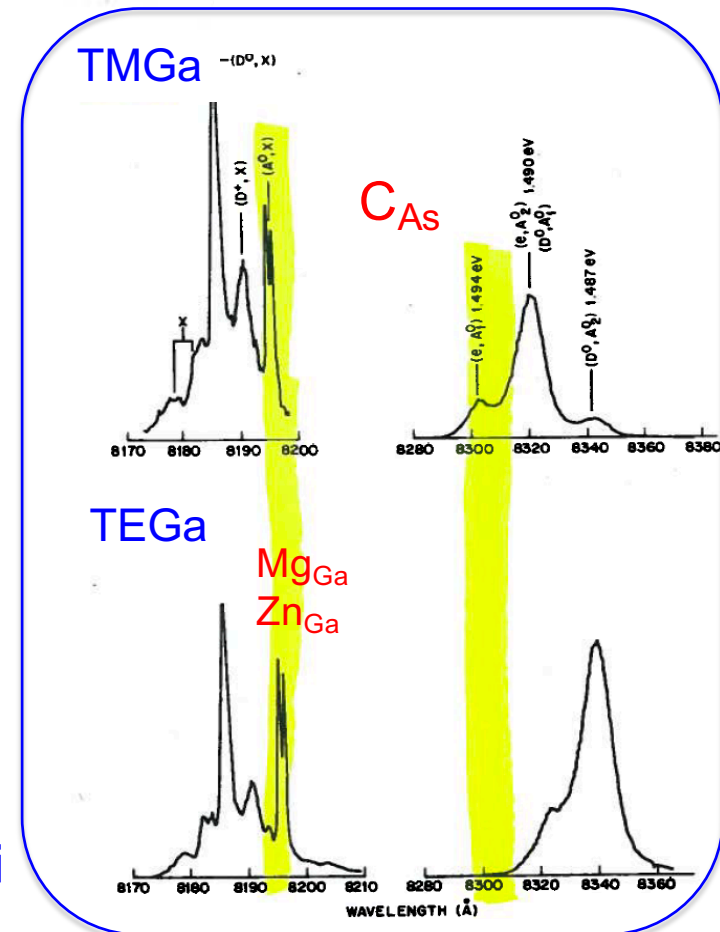
R. Bhat, P. O'Connor, H. Temkin, R. Dingle and V. G. Keramidas

Bell Laboratories, 600 Mountain Ave., Murray Hill, N.J. 07974, USA

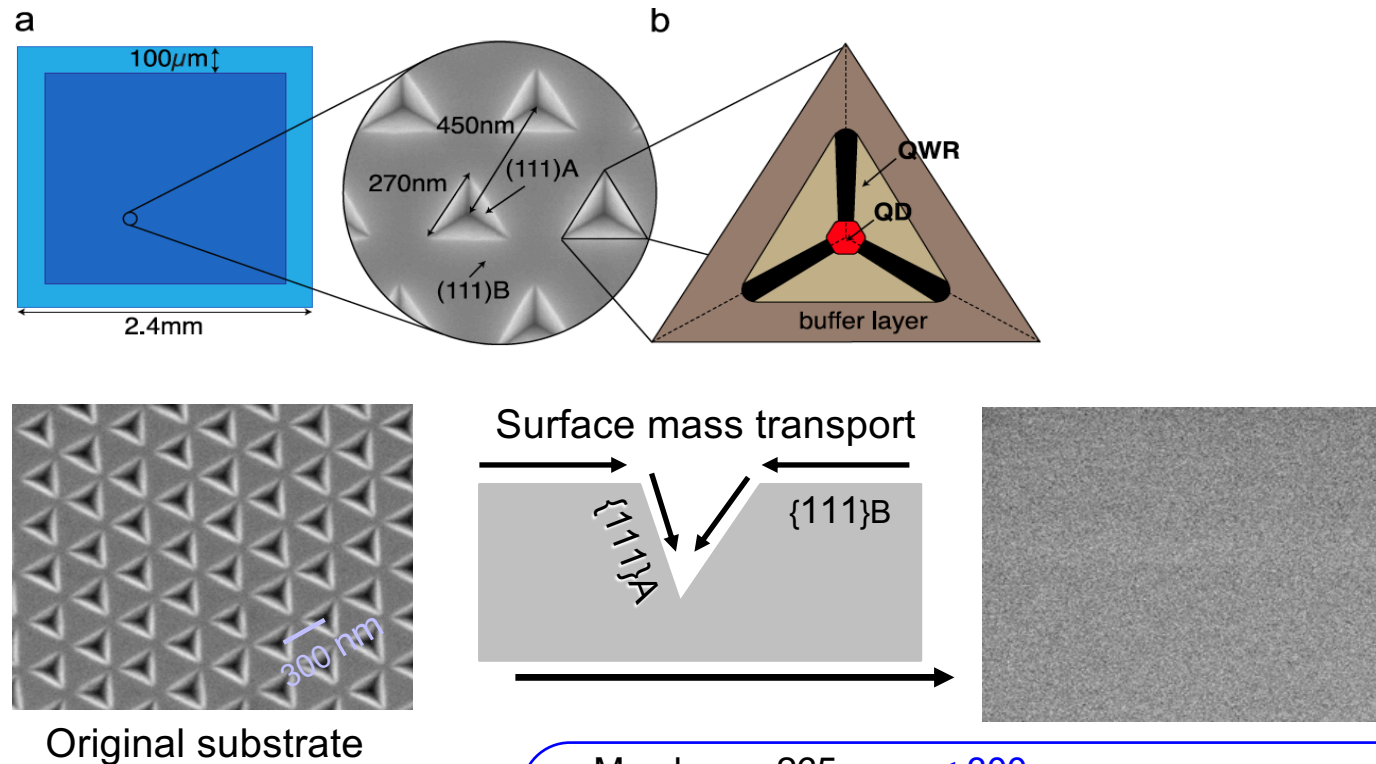
- TMGa: $(\text{CH}_3)_3\text{Ga}$
- TEGa: $(\text{C}_2\text{H}_5)_3\text{Ga}$

- Extrinsic C present with both precursors
- C_{As} with TMGa, NOT with TEGa
- Reduced intrinsic C uptake in (Al)GaAs
- Ga-C bond stronger in TMGa than in TEGa
- TEGa decomposes at lower temperatures

8° K PL
GaAs epi



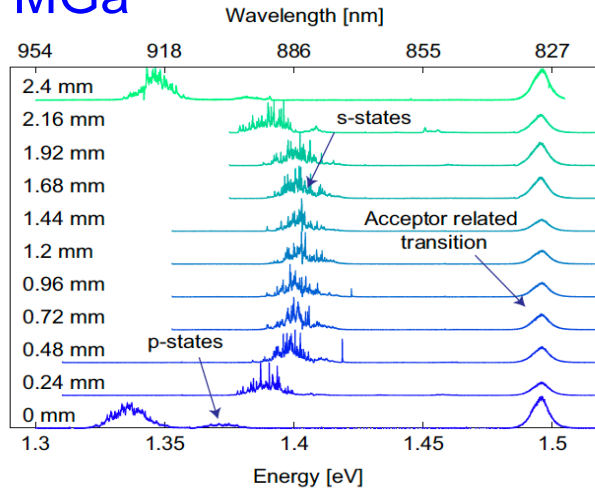
Methyl- vs ethyl- precursors in QDs



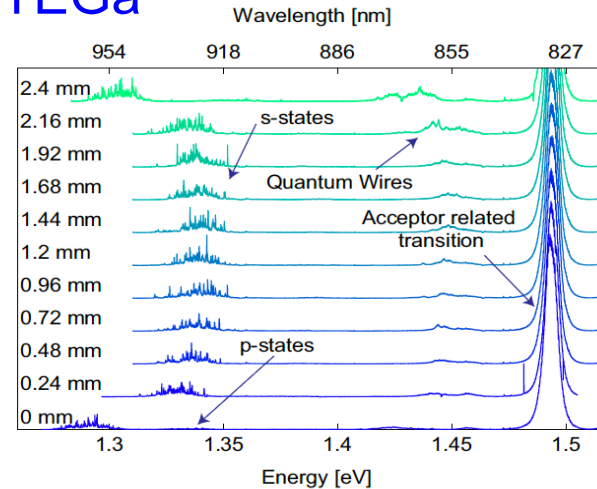
- Membrane 265nm: $s < 300\text{nm}$
- $T < 620^\circ\text{C}$ (otherwise planarization)
- TMGa growth rate varies with T below 600°C – not TEGa
- TMGa decomposes on 111A, not on 111B
- TEGa decomposes on both surfaces > edge effect is reduced
- Reduced C acceptor: improved optical properties

InGaAs/GaAs pyramidal dots: TMGa vs TEGa

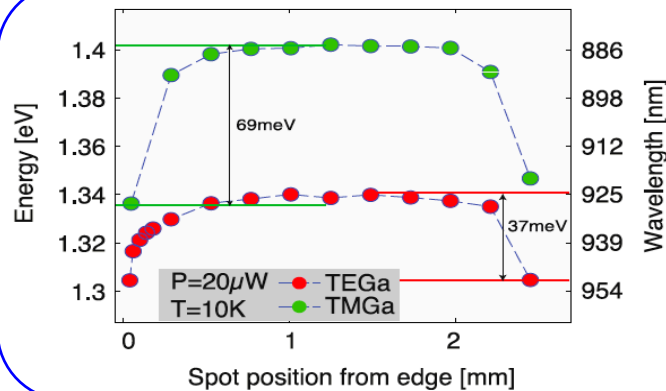
TMGa



TEGa



(+ TMIn)



With TEGa

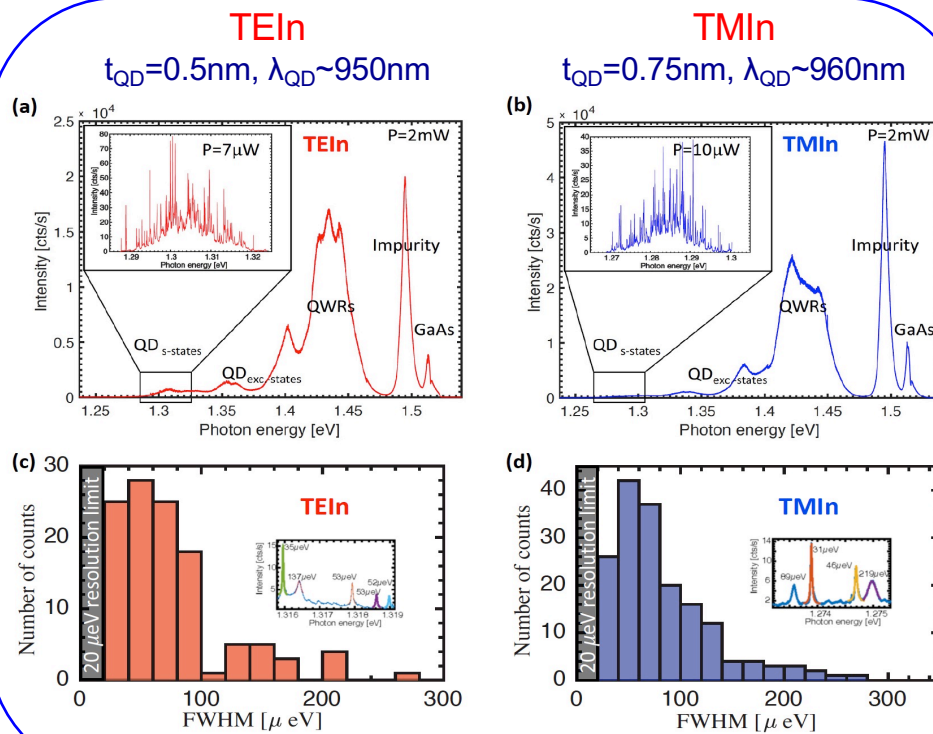
- Longer emission wavelength
- Reduced edge effect : shorter diffusion length
- Better reproducibility : gas diffusion limited

Site-controlled InGaAs/GaAs pyramidal quantum dots grown by MOVPE
on patterned substrates using TEGa

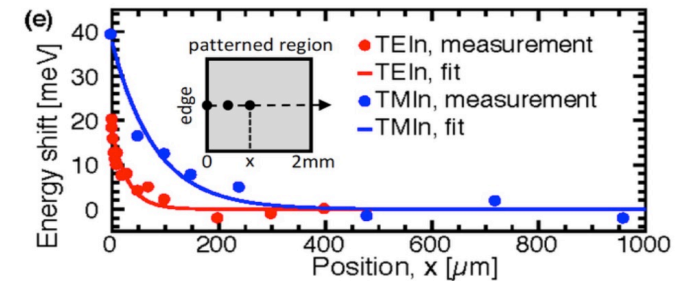
B. Rigal et al., J. Crystal Growth 414 (2015) 187-191

Non-planar growth:
precursors

InGaAs/GaAs pyramidal dots: TMIn vs TEIn (+TEGa)



Variation of QD emission energy across patterned area

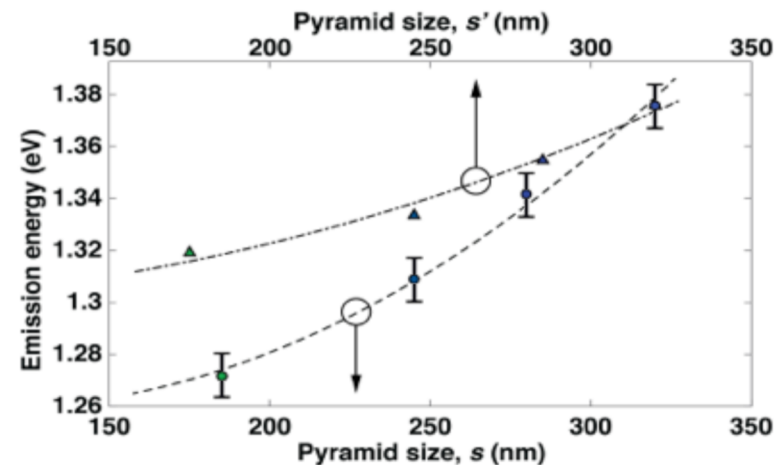
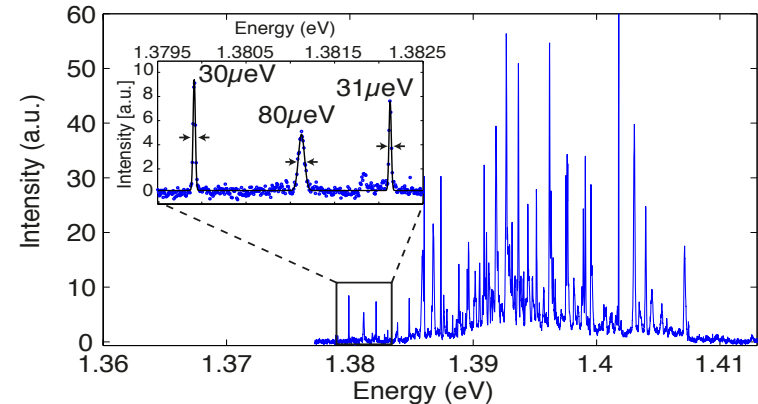


With TEIn:

- Higher incorporation rate of In (compared to TMIn)
- Narrower margins of patterned QD array
- Longer emission wavelengths ($>1\mu\text{m}$) possible

InGaAs QDs arrays - summary

- InGaAs / GaAs QD arrays with 30 μeV PL emission lines & 7 meV inhomogeneous broadening (ensemble of 30-40 QDs)
- 100 meV wavelength tuning through pyramid size variation (210-320nm)
- Spectrally and spatially isolated QDs in uniform matrix
- 40 meV wavelength tuning of isolated QDs
- >>> Multi-wavelength QDs for integrated nanophotonics



Selected experiments in MOVPE

Take away message

- Understand and choose the proper **growth regime**
- **Mass transport** limits the growth rate in a **large temperature range**
- Use the right **precursors** and **carrier gas**
- Understand the **dynamics** of the growth process
- Taylor **smart surfaces** (vicinals, planar & non-planar patterns...)
- Make use of **surfactants**

Master the science & **art** of building new crystals atom by atom:
Epitaxy