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TE/TM polarisation response of InAs/GaAs quantum dot bilayers

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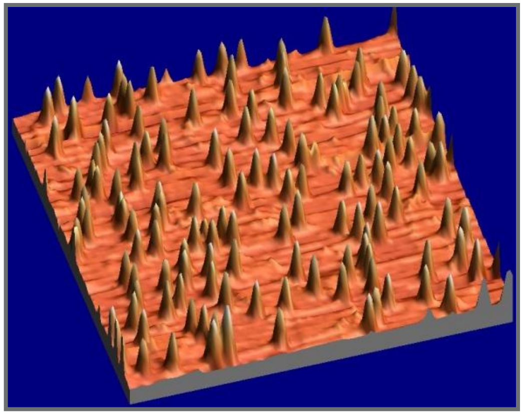
Growth of InAs/GaAs quantum dots

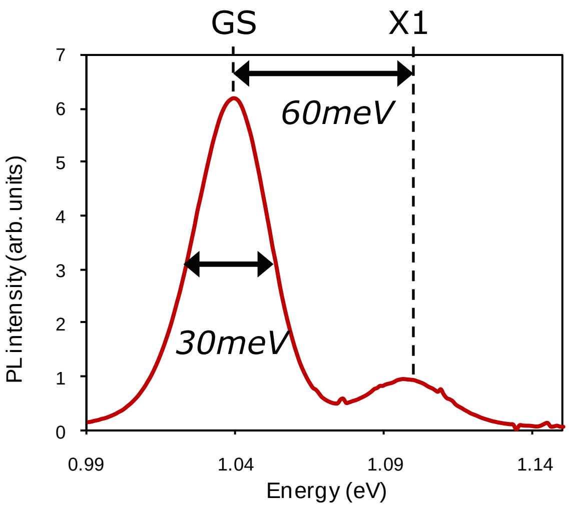
InAs is deposited onto a GaAs(001) surface by MBE

Growth occurs by the Stranski-Krastanov process:

- Initial growth forms a 2D layer (wetting layer)
- After 1.7 monolayers, 3D dots form
- Size, shape & composition determined by growth parameters
- QDs capped by GaAs



1μm x 1μm AFM

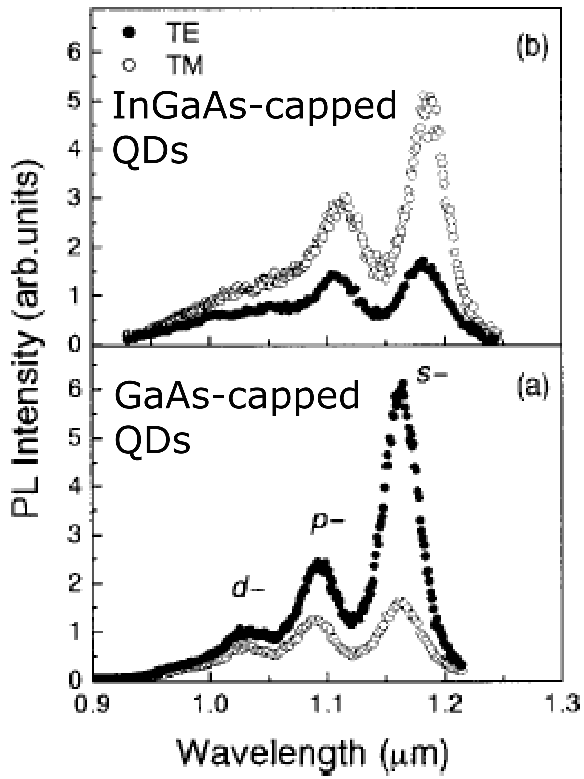


Polarisation control of InAs/GaAs quantum dots

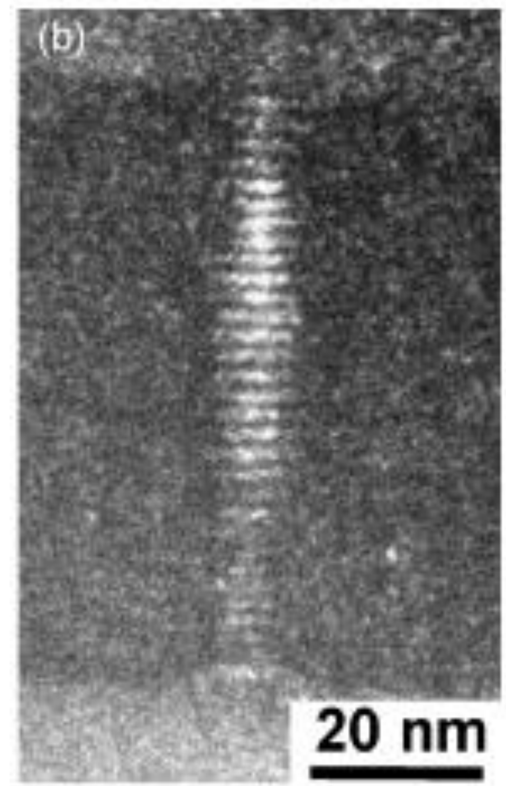
Polarisation-insensitive operation is desirable for device applications e.g. optical amplifiers

Strategies to achieve polarisation-insensitive response from QDs include:

- InGaAs capping
  - increased QD height
- Stacked QDs/ columnar QDs
  - electronic coupling between QDs
  - increased extent of wavefunction in growth direction



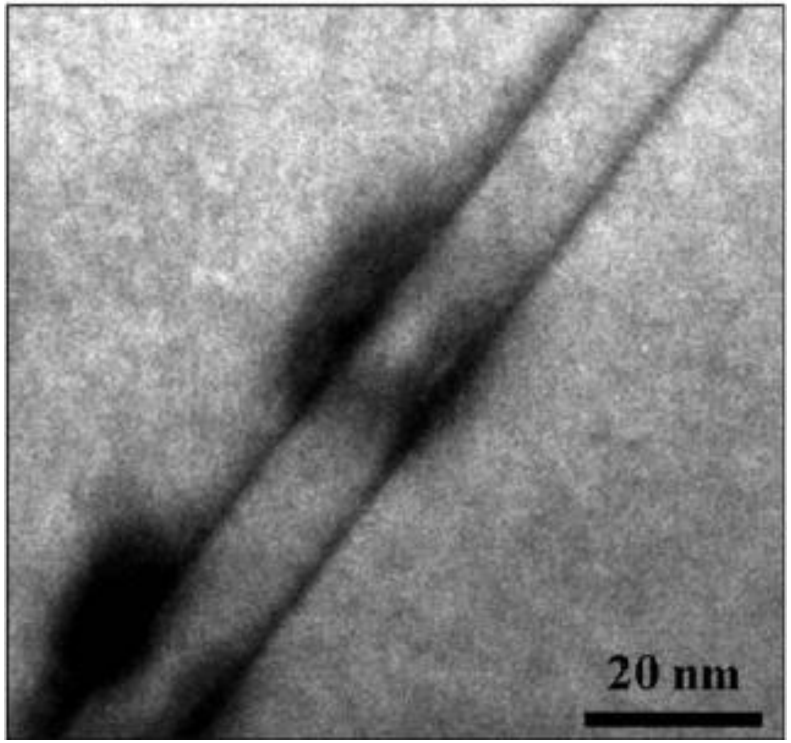
Jayavel *et al.* APL **84**, 1820 (2004)



Ridha *et al.* JQE **46**, 197 (2010)

InAs/GaAs quantum dot bilayers

- Use the first (seed) layer as a template to set the density of the second layer
- QDs in upper layer will nucleate above seed layer QDs
- Improved control of growth conditions (particularly temperature) for upper layer to achieve long wavelength emission
    - suppress In/Ga intermixing ✓
    - maintain QD size ✓



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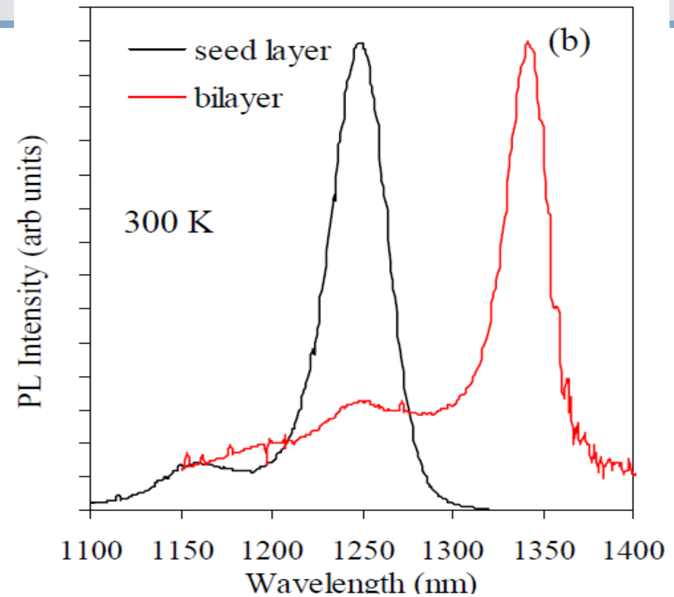
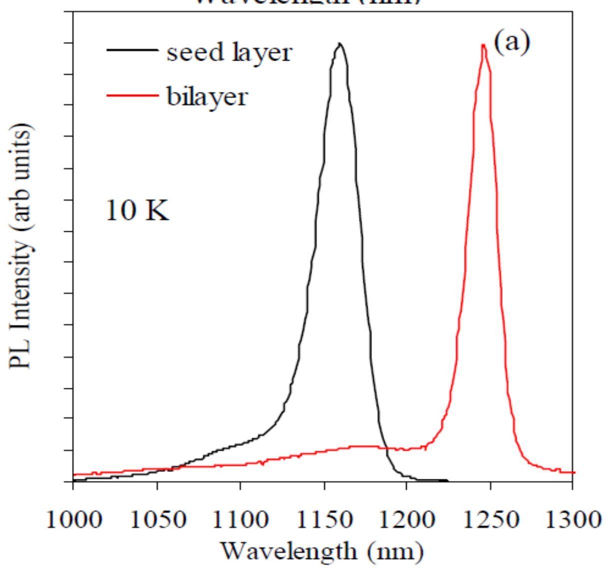
InAs/GaAs quantum dot bilayers

- Emission wavelength of upper layer significantly extended compared to single layer
- Highly uniform QDs: extremely low inhomogeneous broadening (14 meV at 10 K)
- Electronic coupling between layers leads to suppression of seed layer emission
- Room temperature ground state emission up to 1400 nm for GaAs-capped bilayers, can be extended to >1500 nm with InGaAs capping





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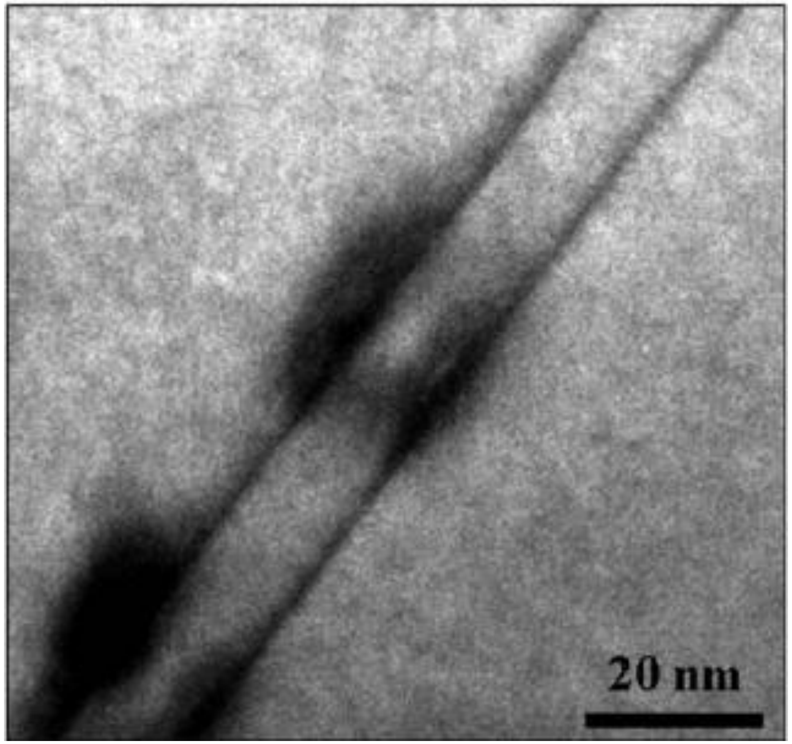
Considerations for bilayer QD polarisation response

What influence will bilayer structure have on their polarisation response?

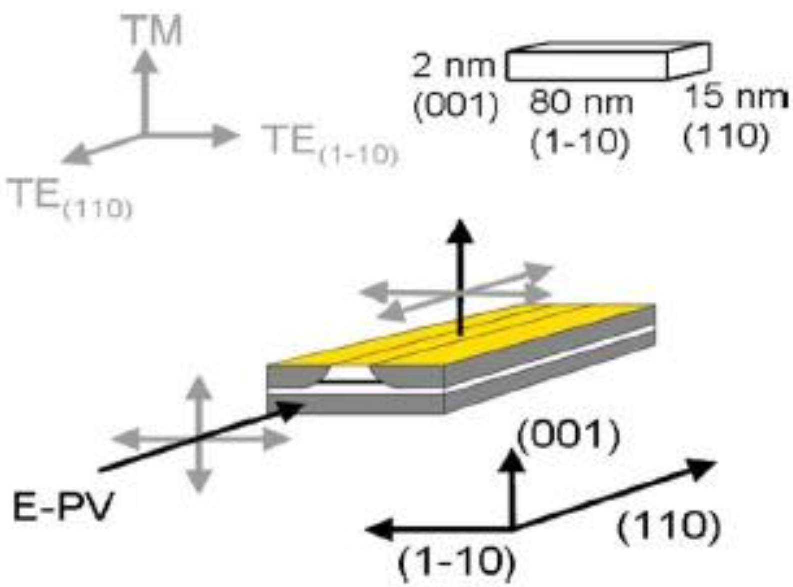
• Increased size of upper layer QD: will this enhance the TM component?

• QDs are electronically coupled but rapid relaxation to lowest energy states results in carrier localisation in upper QD

• What effect does InGaAs-capping of the upper layer have on its polarisation properties?



Photovoltage measurements



Heck *et al.* JQE **45**, 1508 (2009)

- Focus polarised light onto facet of QD laser and measure photovoltage
- Relatively simple technique
- Polarisation-insensitive signal from GaAs barrier provides calibration

Characterisation of a variety of QD laser structures containing QDs grown under different conditions:

- Seed layers only
- GaAs-capped bilayers
- InGaAs-capped bilayers

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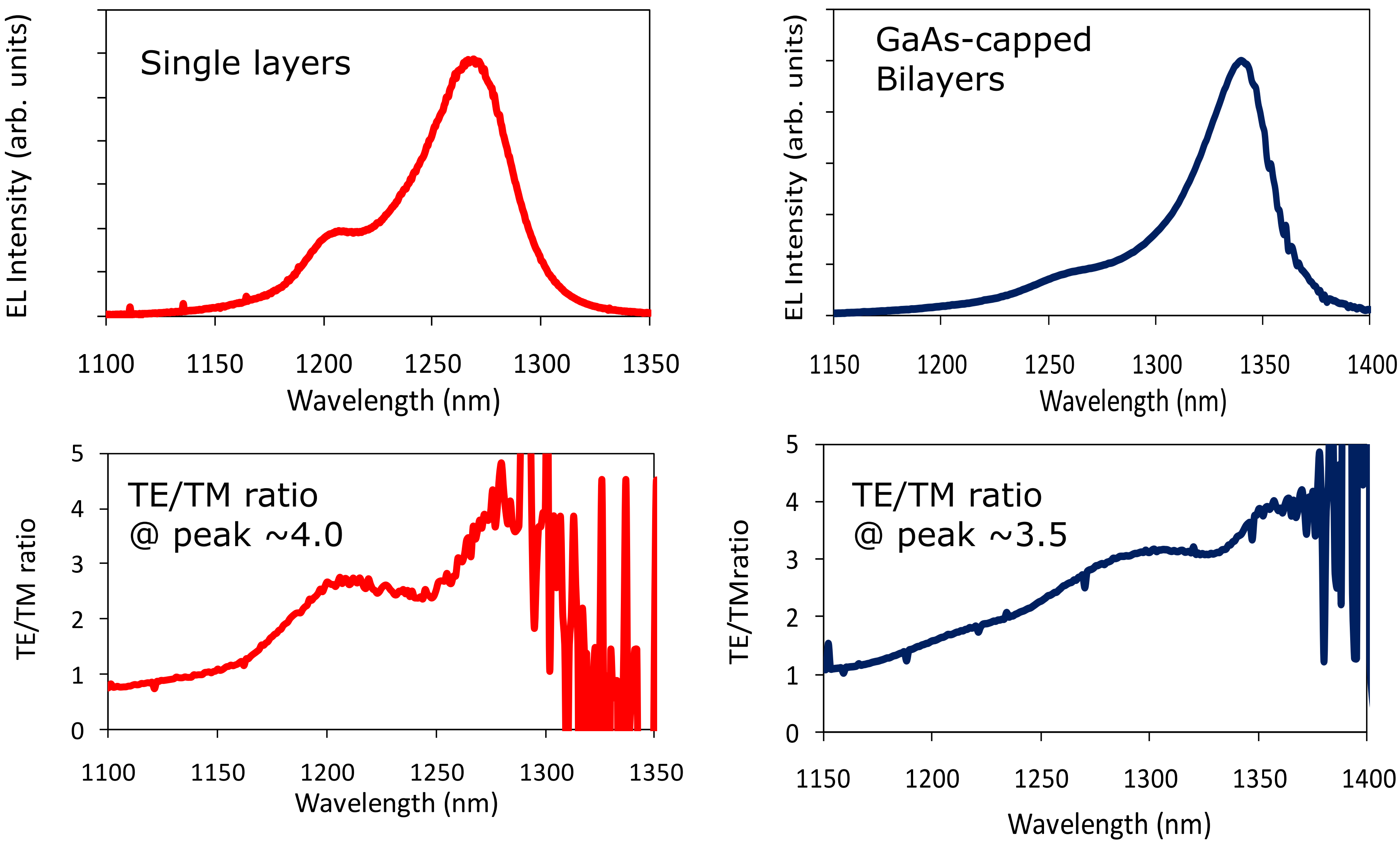
Polarisation response: single layers vs. bilayers



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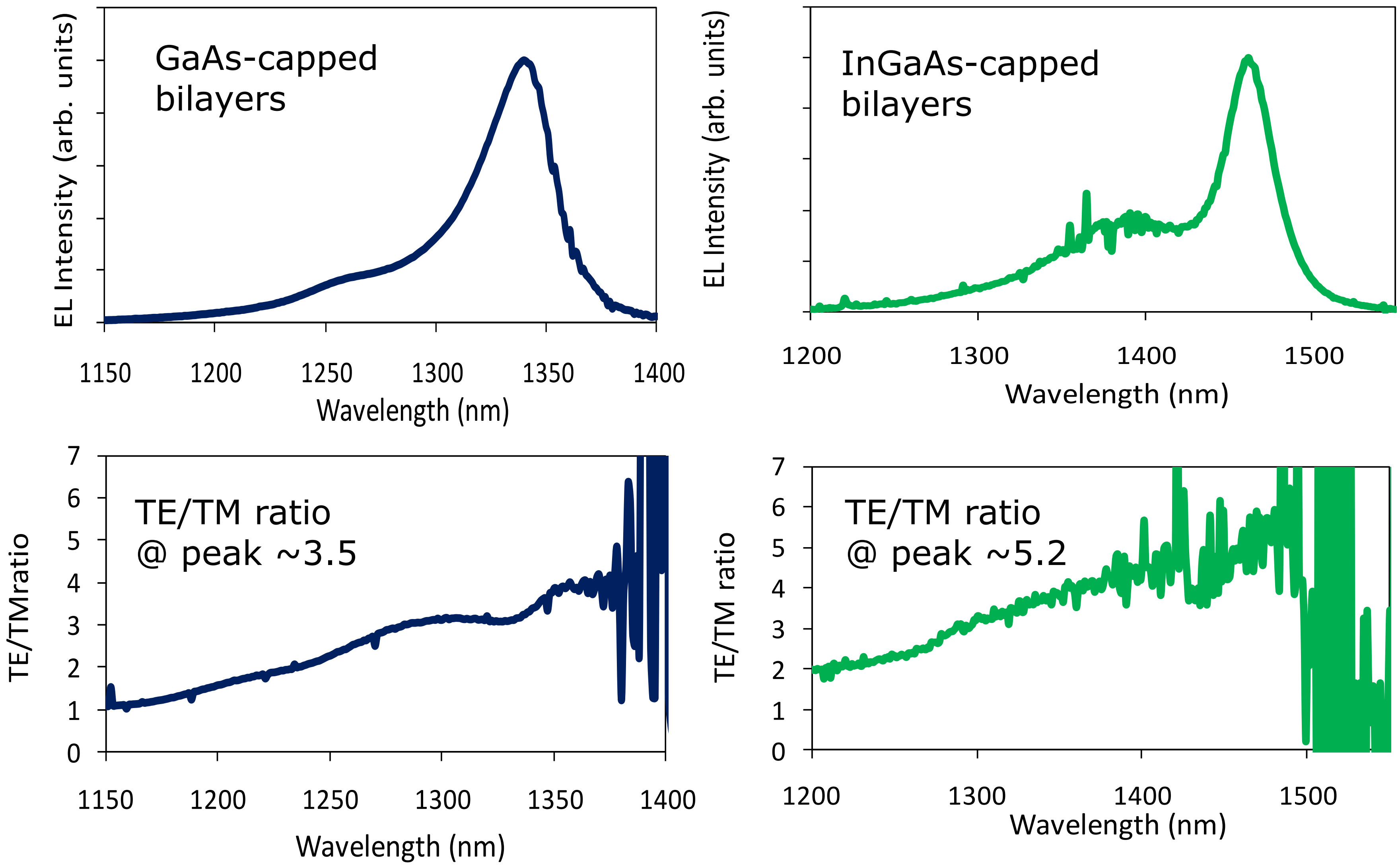
Polarisation response: effect of InGaAs cap



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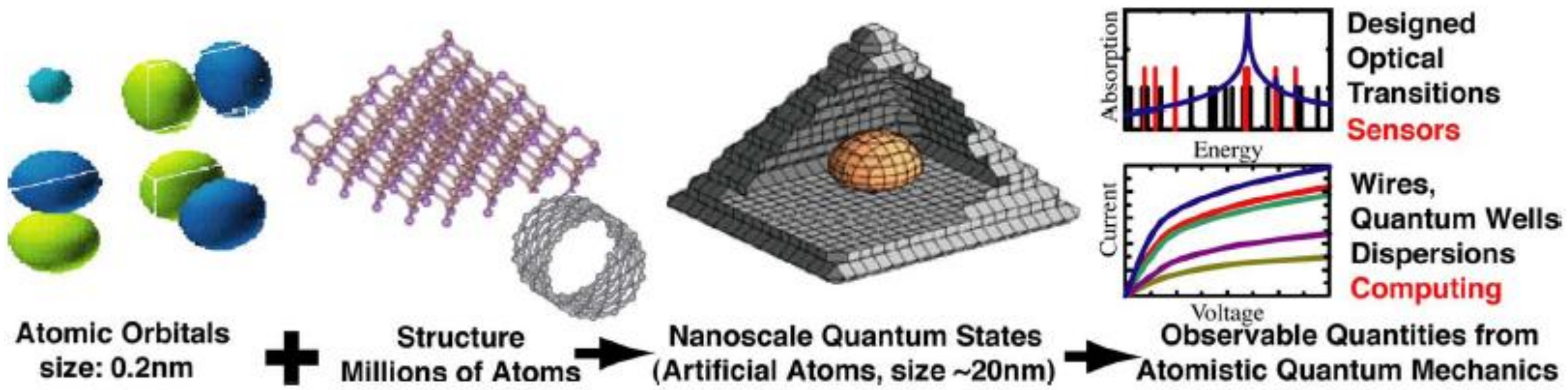
Atomistic modelling with NEMO 3-D



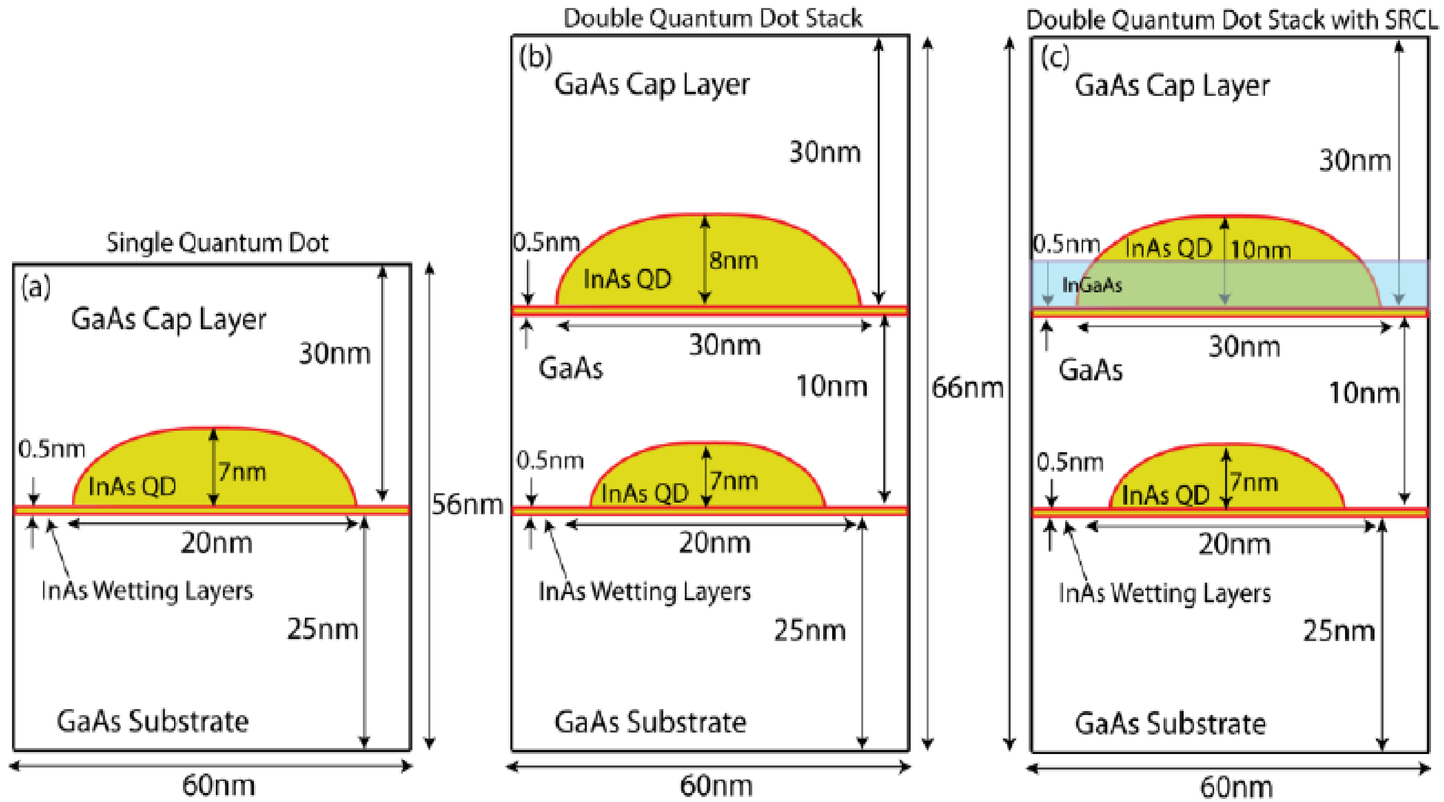
- Multi-million atom simulations based on 20-band sp3d5s* nearest neighbour empirical tight binding model

- Strain calculated using atomistic Valence Force Field model, with modified Keating potential including anharmonic corrections

- Includes linear and quadratic piezopotentials

Klimeck *et al.* IEEE Trans. Electron. Devices **54**, 2079 (2007)
Usman *et al.* IEEE Trans. Nano. **8**, 330 (2009)

Model QDs



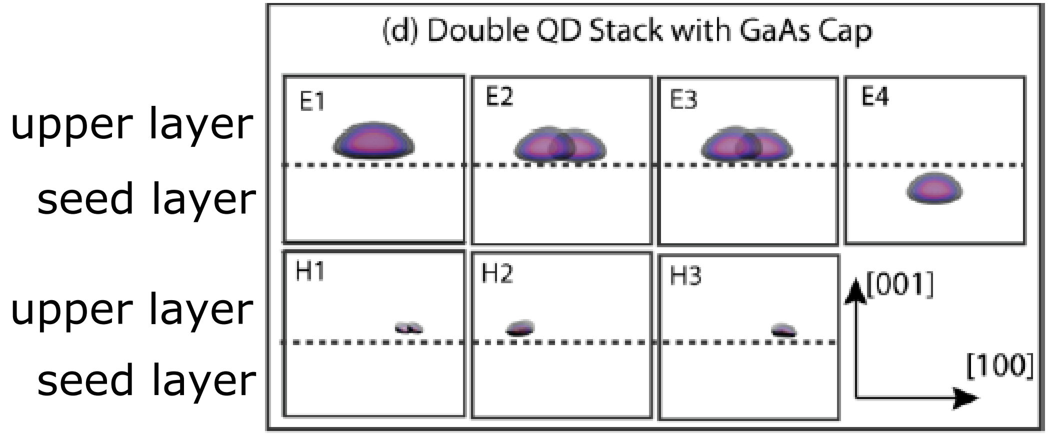
- Large strain & electronic domains (15 and 10 million atoms respectively)
- QD sizes estimated from transmission electron microscopy
- Considering pure InAs QDs – no compositional gradients

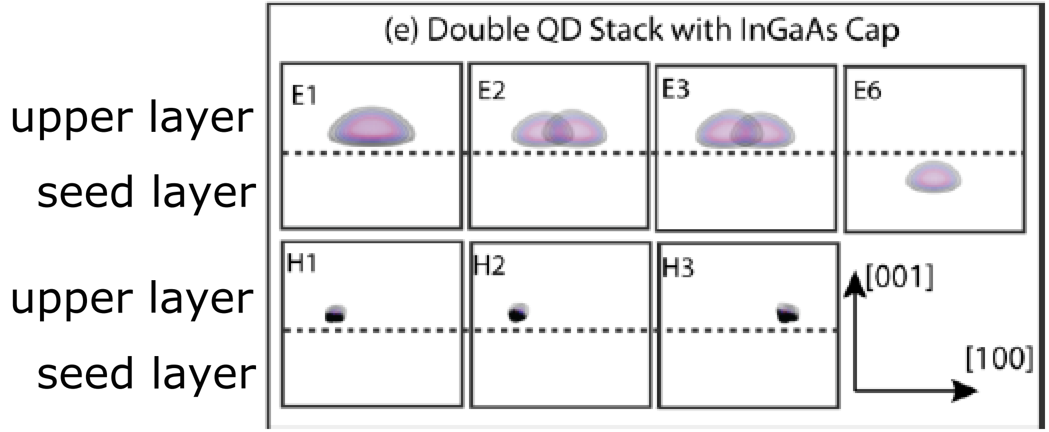
Wavefunction modelling with NEMO 3-D

- Modelling confirms localisation of electrons and holes in upper layer QDs in bilayers

- Lowest three electron states in GaAs-capped bilayer reside in upper QD, fourth energy level is in seed layer

- For InGaAs-capped bilayer, the lowest five electron states are in the upper QD





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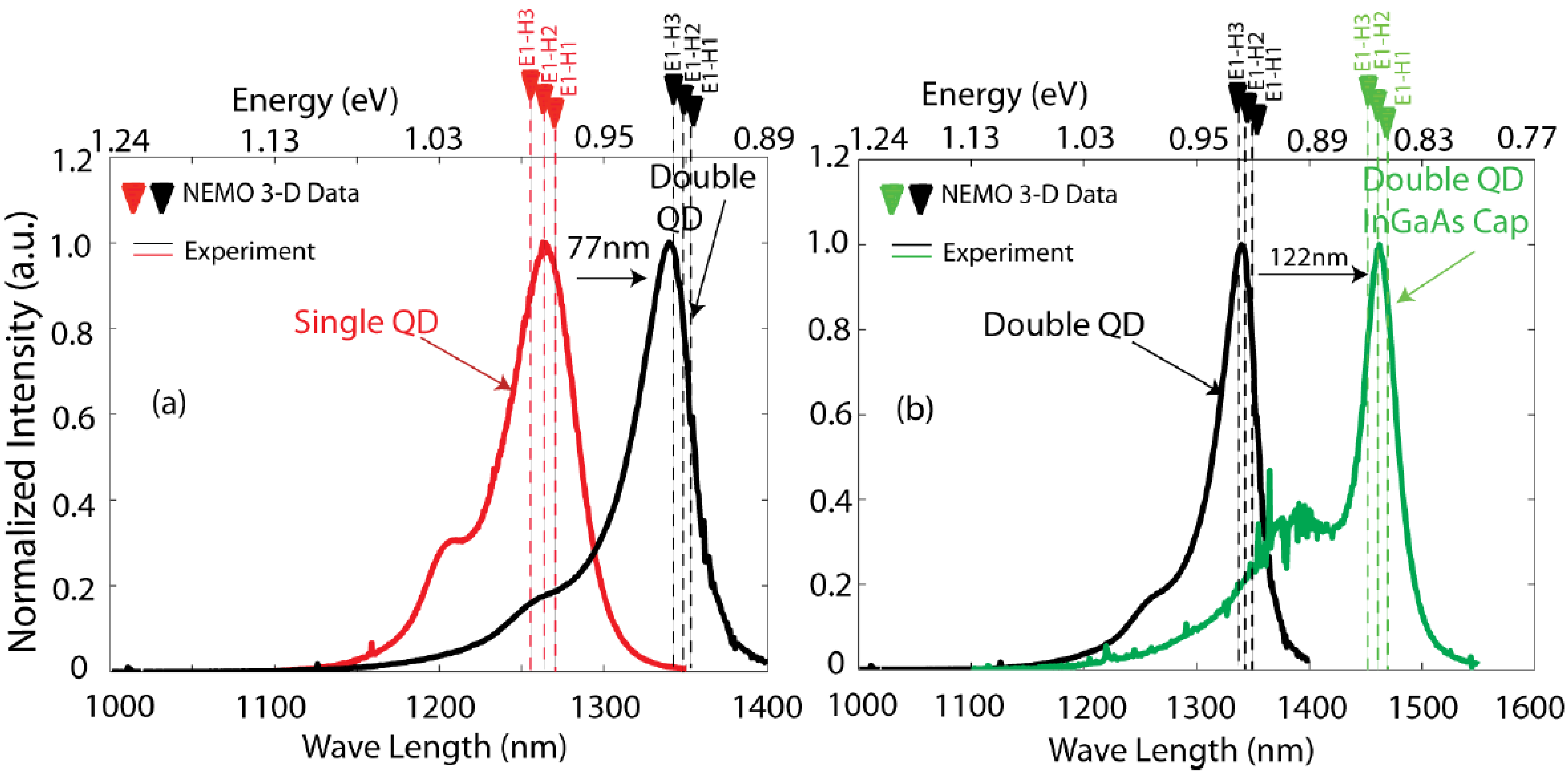
Transition energies



• Good agreement between ground state transition energies from the model and measured electroluminescence

• Multiple closely-spaced hole levels can contribute to ground state emission

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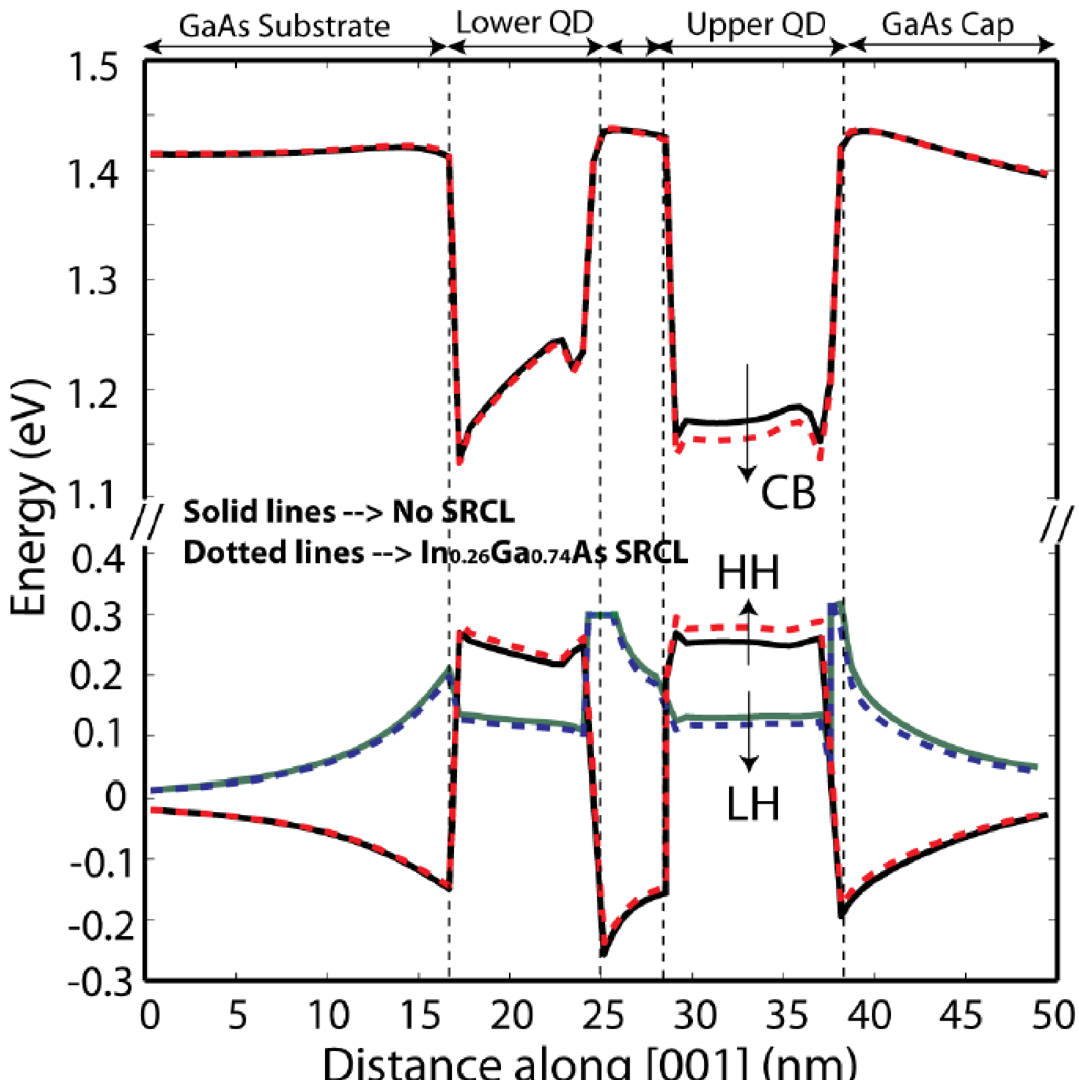
Effect of InGaAs-capping

- Calculated local band edges in GaAs-capped and InGaAs-capped bilayer QDs

- InGaAs cap reduces hydrostatic strain and increases biaxial strain, shifting CB and HH band edges → extended emission wavelength

- Reinforcement of biaxial strain increases splitting between HH and LH states → ground state will have increased HH character



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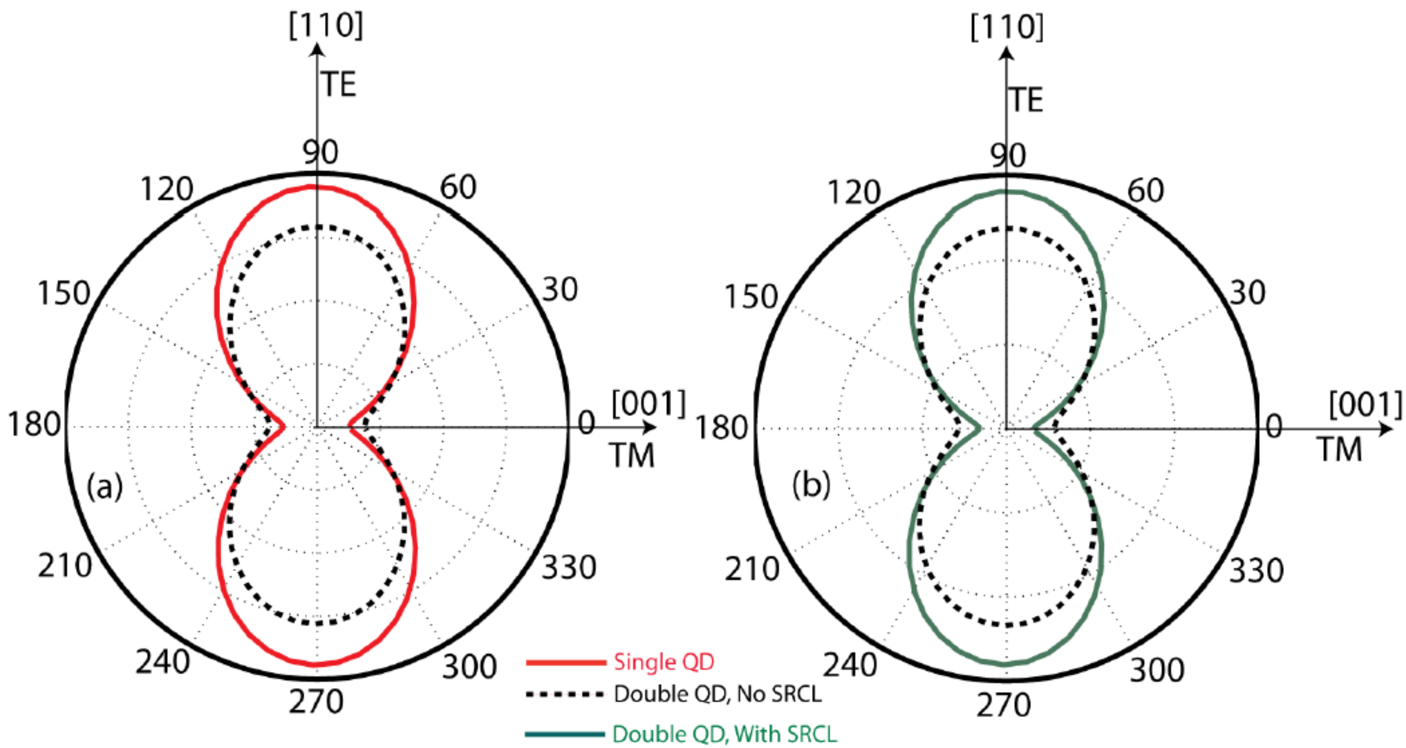
TE-TM polarisation response



- Calculated interband optical transition intensities as function of angle between [110] and [001]
- Sum of intensities of E1-H1, E1-H2, E1-H3 transitions
- Increased QD height in GaAs-capped bilayer compared to single layer enhances TM optical mode
- Increased HH character of hole states in InGaAs-capped bilayer enhances TE and suppresses TM modes compared to GaAs-capped bilayer

Conclusions

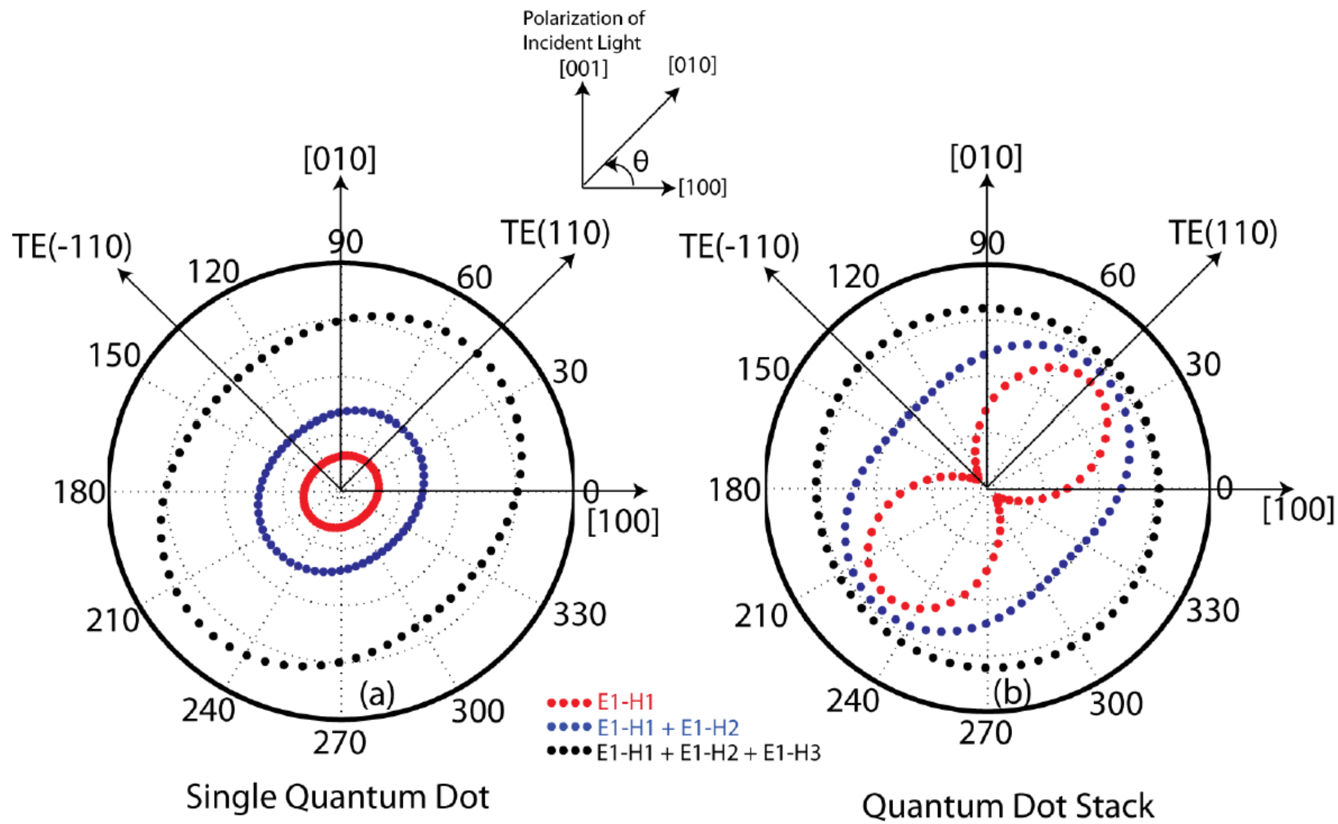
- Slight reduction in polarisation anisotropy for GaAs-capped QD bilayers compared to single QD layers due to increased size of the upper layer QD

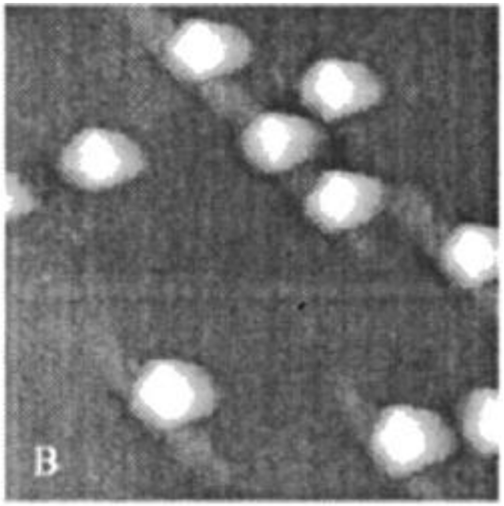
- When the upper layer of the bilayer is InGaAs-capped, a significant increase in the polarisation anisotropy is observed, in contrast to reports for single layers

- This increase in polarisation anisotropy is due to increased splitting between heavy hole and light hole bands $\rightarrow$ increased heavy hole character of hole ground states

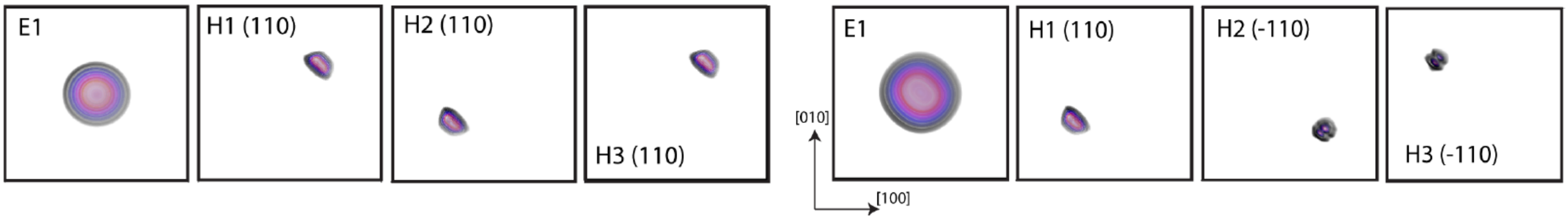
- Future work: examine influence of InGaAs-cap thickness and composition using polarisation-resolved photoluminescence

[110] / [1-10] polarisation response





Le Ru *et al.* PRB **67**, 165303 (2003)



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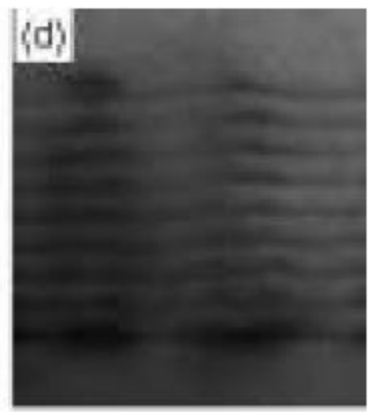
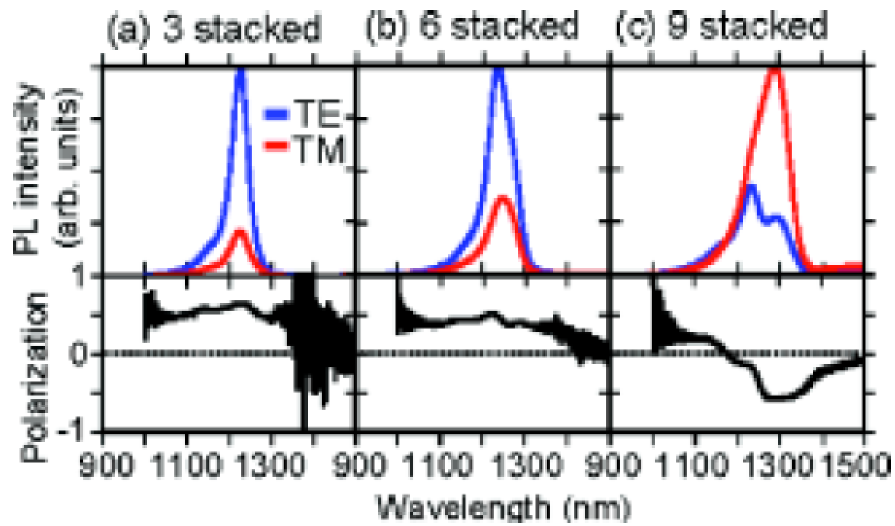
Polarisation control in stacked QDs

Inoue *et al.* APL **96**, 211906 (2010)

Stacked InAs QD layers with 4.5 nm GaAs spacer layers

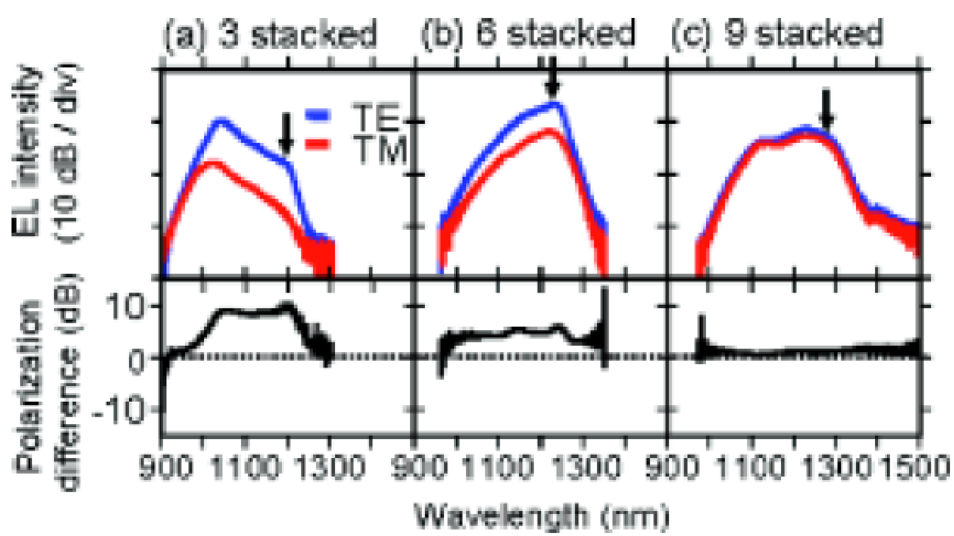
QD size control by altering InAs coverage: 1st layer 2.6 ML, others 1.9 ML





Increased TM component with increasing number of layers due to electronic coupling

Degree of polarisation becomes negative in PL for 9 QD layers, but polarisation insensitive EL due to reduced coupling to waveguide for TM



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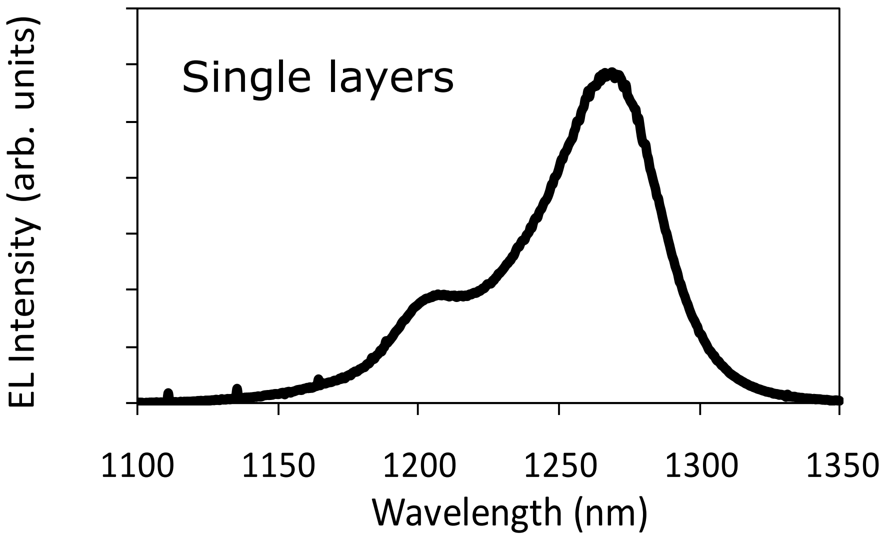
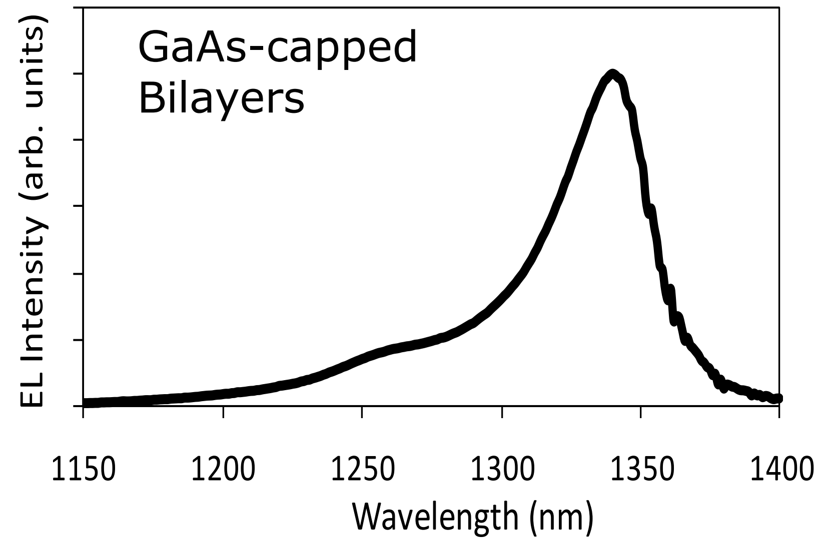
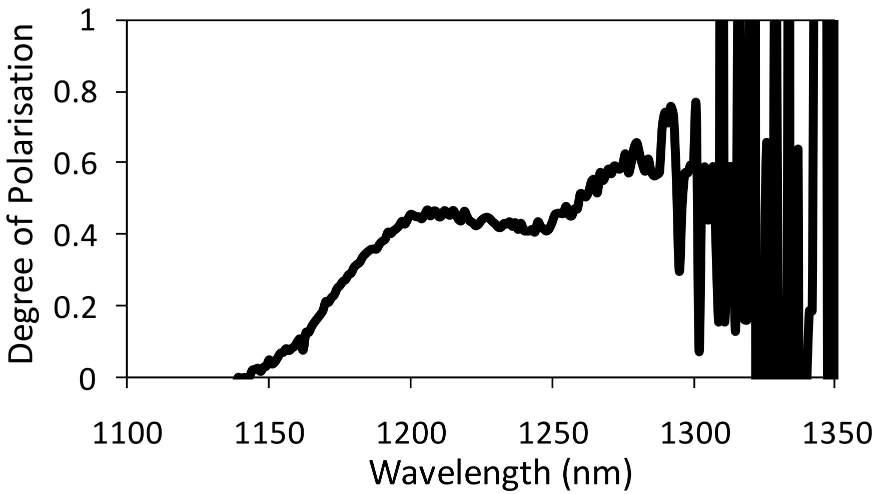
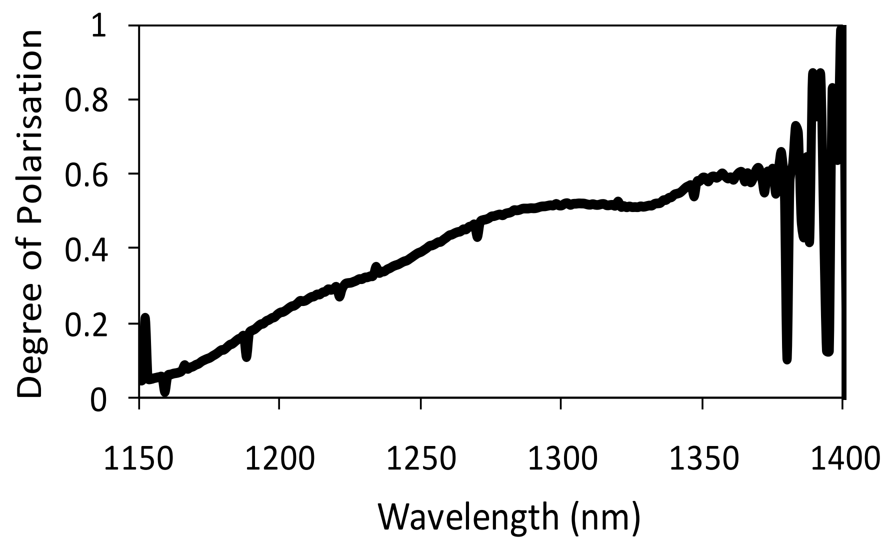
Degree of polarisation $= \frac{I_{TE} - I_{TM}}{I_{TE} + I_{TM}}$

Polarisation response: single layers vs. bilayers









Degree of polarisation $= \dfrac{I_{TE} - I_{TM}}{I_{TE} + I_{TM}}$

Polarisation response: effect of InGaAs cap