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Methods for Fabrication of Quantum Dots

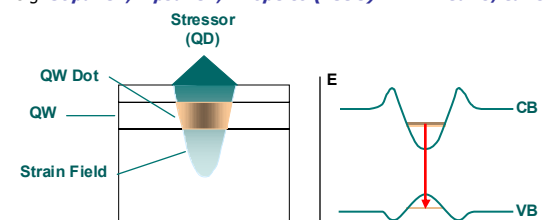
- Lithographically patterning substrates, etching, and regrowth
 - Lithography** – optical, X-ray, electron beam, focused ion beam
 - Etching** – chemical, reactive ion etching
 - Regrowth** – MOCVD, MBE
- Sugiyama, Sokuma, Muto, Yokoyama (1995): InGaAs/GaAs QD's
 - Advantages:** precisely control size, achieve desired structures
 - Disadvantages:** relatively large dot size (> 50 nm), low dot density, easy to be contaminated & to form defects

Methods for Fabrication of Quantum Dots

- Self-assembled QD's (Stranski-Krastanow growth)
 - Madhukar, Xie, Chen, Konkar (1994); Solomon, Trezza, Harris (1995): InAs/GaAs QD's
 - Advantages:** easy to be fabricated, small dot size, high density (10^{11} cm^{-2})
 - Disadvantages:** large size fluctuation ($\pm 10\%$)
 - $\sim 50 - 100 \text{ meV}$ in linewidth for self-assembled InAs/GaAs QD's

Strain-Induced Quantum-Well Dots

e.g. Sopanen, Lipsanen, Ahopelto (1995): InP:InGaAs/GaAs



- Advantages:** reduced nonradiative recombination rate, reduced size fluctuation
 - To greatly improve performance of corresponding optoelectronic devices, e.g. QWD lasers

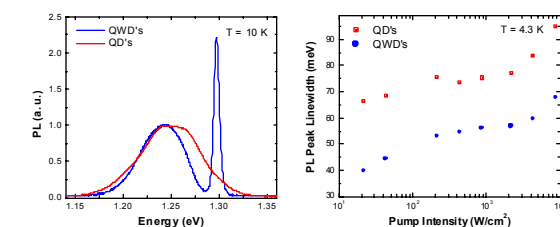
Previous Work

- InGaAs/GaAs QW strained by InP Q. dots
 - Sopanen, Lipsanen, Ahopelto (1995)
- GaInP/AlGaInP QW strained by InP Q. dots
 - Sopanen, Taskinen, Lipsanen, Ahopelto (1996)
- Optically-pumped laser based on coupled InP quantum dot and InGaP quantum well in InP-InGaP-In(AlGa)P-InAlP heterostructures
 - Walter, Holonyak, Ryou, Dupuis (2001)
- Spatial distribution of strain field induced by QD's depends on width & period of stressors, thickness of cap layer, & total thickness of QW
 - Xu & Petroff (1991)
 - InP – used as stressors**
 - InP Q. dots – not capped**

Our Recent Work

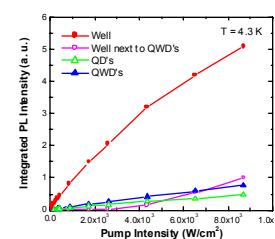
- InGaAs/GaAs QWD's – fabricated by using self-assembled InAs QD's as stressors
- Measurements of photoluminescence spectra – effective technique to study InAs:InGaAs/GaAs QWD's
- Comparison with InAs/GaAs QD's – made: QWD's – significantly-improved nanostructures over QD's
 - Spatial uniformity**
 - Intensity dependences**
 - Band-filling effects**

Comparison of PL Peak Linewidths



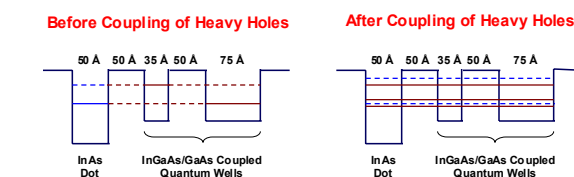
- PL linewidth for QWD's is narrower than that for QD's by 26 meV

Wavelength-Integrated PL Intensity vs. Pump Intensity



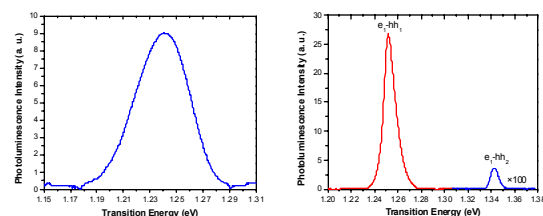
- PL intensity for QWD's is higher than that for QD's by ~ 1.85
 - Higher carrier capture rate by QW**
 - Reduced nonradiative recombination rate**

Coupling between InAs Dots & Coupled Quantum Wells



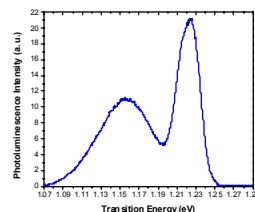
- Both well-like & dot-like transitions – novel quantum dots due to 3-D confinement of carries

InAs Quantum Dots vs. InGaAs/GaAs Coupled Quantum Wells



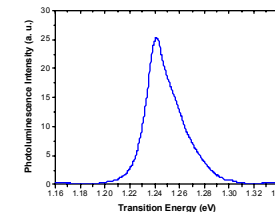
- Dot transition – almost aligned to lowest well transition

Coupling between Q. Dots & Coupled QW's (Dot is next to Narrow Well): Dot Level is below Lowest QW Level



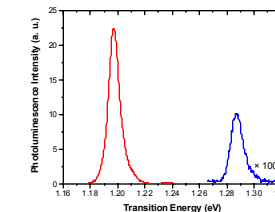
- Due to mixing of dot & well states, well-like transition – much broader linewidth
- Dot-like transition – significantly broadened on low-energy side due to spatially-inhomogeneous strain fields parallel to surface normal inside wide well applied by QD's

Strongest Coupling between Q. Dots & Coupled QW's (Dot is Next to Narrow Well): Dot Level is Aligned to Lowest QW Level



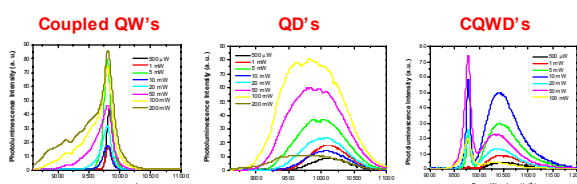
- Broad linewidth – due to superposition of two transitions
- Much broader linewidth on high-energy side (much narrower than QD's) – due to size fluctuation of quantum dots & spatially-inhomogeneous strain fields induced by quantum dots with smaller sizes inside wide well

Coupling between Q. Dots & Coupled QW's (Dot is Next to Wide Well): Dot Level is above Lowest QW Level



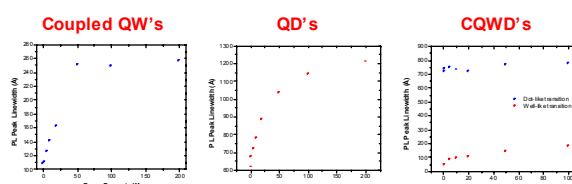
- Dot-like transition – not observable due to broad linewidth
- Lowest transition – same linewidth as that for coupled quantum wells: negligible spatial inhomogeneity of strain fields applied to quantum wells inside wide well
- 2nd well-like transition – sizeable linewidth broadening since heavy hole – sensitive to spatially-inhomogeneous strain fields applied to quantum wells inside narrow well by quantum dots; peak intensity – relatively stronger as a result of coupling with quantum dots

Comparison among Three Different Nanostructures



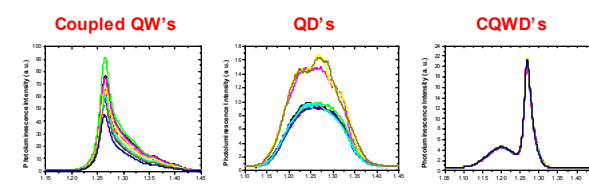
- CQW's:** As pump power increases, high-energy shoulder grows due to population of states in 2-D subband
- QD's:** As pump power increases, carriers fill up QD's with smaller sizes
- CQWD's:** As pump power increases, well-like transition picks up strength

PL Peak Linewidth vs. Pump Power



- While linewidths for both CQW's and QD's increase as pump power increases, linewidths for both dot-like and well-like transitions stay same!
 - Both dot-like and well-like states are truly confined in 3D's!**

PL Spectra at Different Lateral Locations



- CQW's:** peak intensity & linewidth change by 70% and 17%
- QD's:** peak intensity & linewidth change by 64% and 48%
- CQWD's:** peak intensities of well-like & dot-like transitions only change by 9.1% and 6.5%

Conclusion

- Coupling between quantum dots and coupled quantum wells – investigated
- Three coupling regimes – established
- Spatially-inhomogeneous strain fields applied by quantum dots to quantum wells – evidenced
- Novel "quantum dots" by linear superposition of wave functions for InAs dots and coupled QW's: sharp QW-like linewidth on low-energy or high-energy side – observed; higher carrier capture & escape rates – expected

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