

Simulation of the Quantum-Confined Stark Effect in a Single InGaN Quantum Dot

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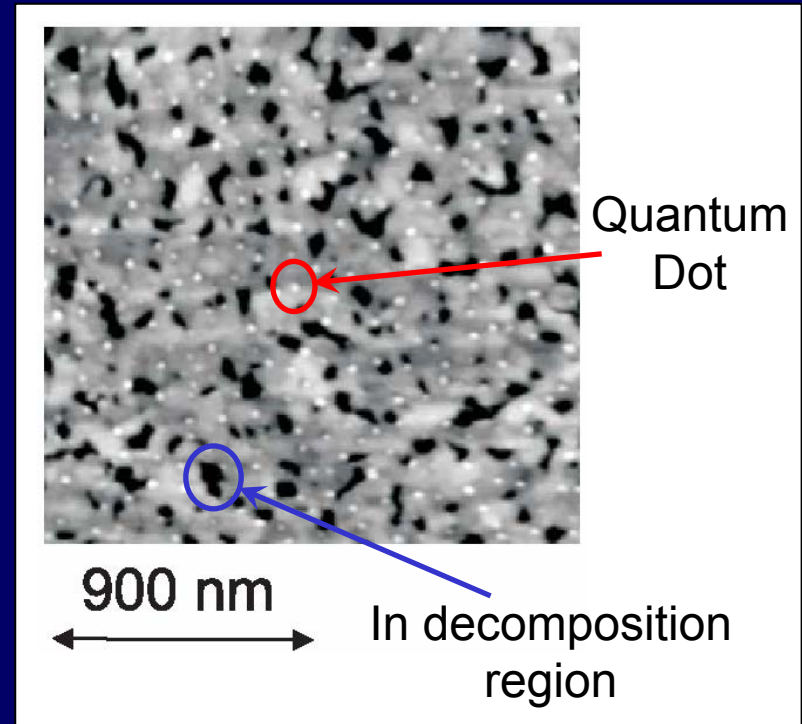
Talk Outline

- InGaN quantum dots (QDs)
 - Growth
 - Sample structure
- Experimental Measurement
 - Photoluminescence (PL) setup
 - PL measurement with laterally applied electric field
- Computational Modeling
 - **nextnano³**
 - Modeling results
 - Comparison with experiment

InGaN Quantum Dots

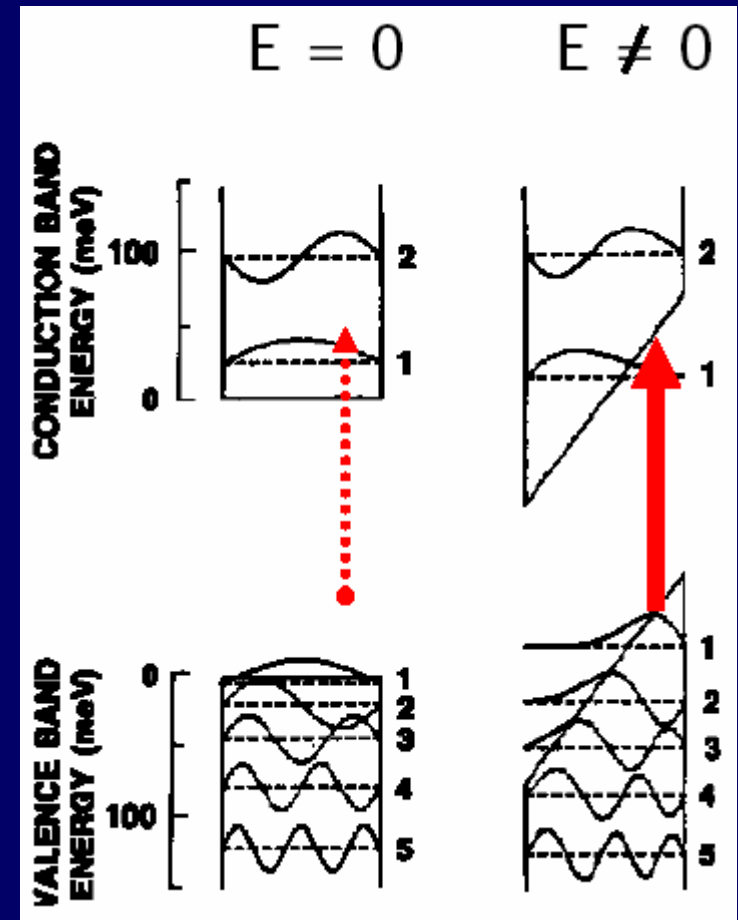
- III-Nitrides
 - Blue/UV optoelectronic devices:
 - Solid state lighting
 - High density information storage
- InGaN QD
 - Applications in laser diode
 - low threshold current
 - Narrow linewidth
 - Cavity quantum electrodynamics (CQED)
- Growth
 - Metal-organic vapor phase epitaxy (MOVPE)
 - Post growth N₂ anneal
 - Induces QD formation via 'modified droplet epitaxy' process (In spinodal decomposition) [1]

[1] R.A. Oliver, et al., APL 83 (4), 755, 2003



Quantum Confined Stark Effect

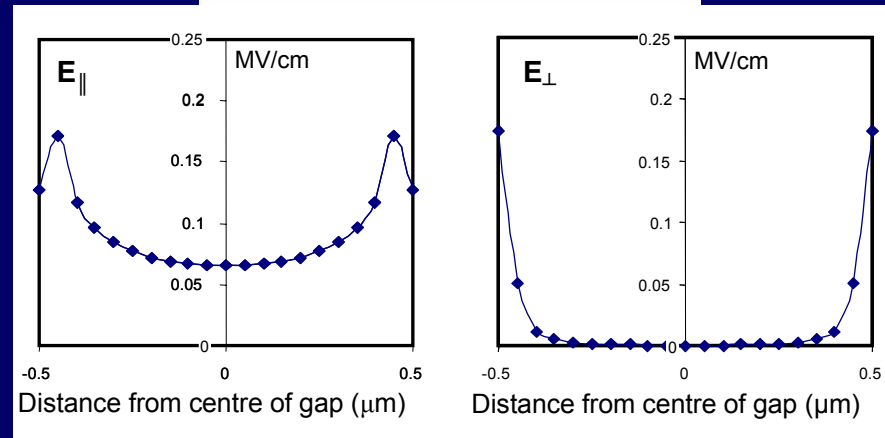
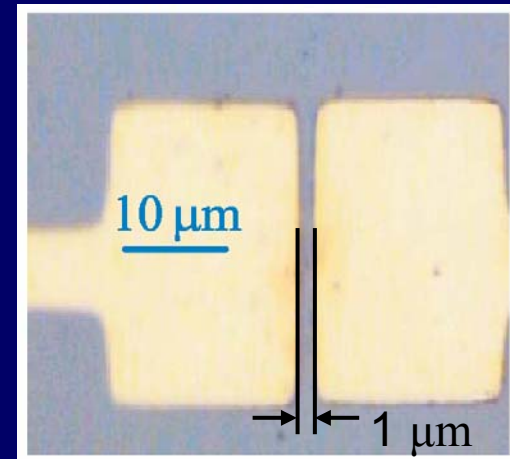
- Change in band structure due to an applied electric field
 - Reduction in energy of localized states
 - Reduces electron-hole overlap
- InGaN - arises due to built-in piezoelectric field
 - Quite large ~ 2 MV/cm
 - QCSE along the growth direction



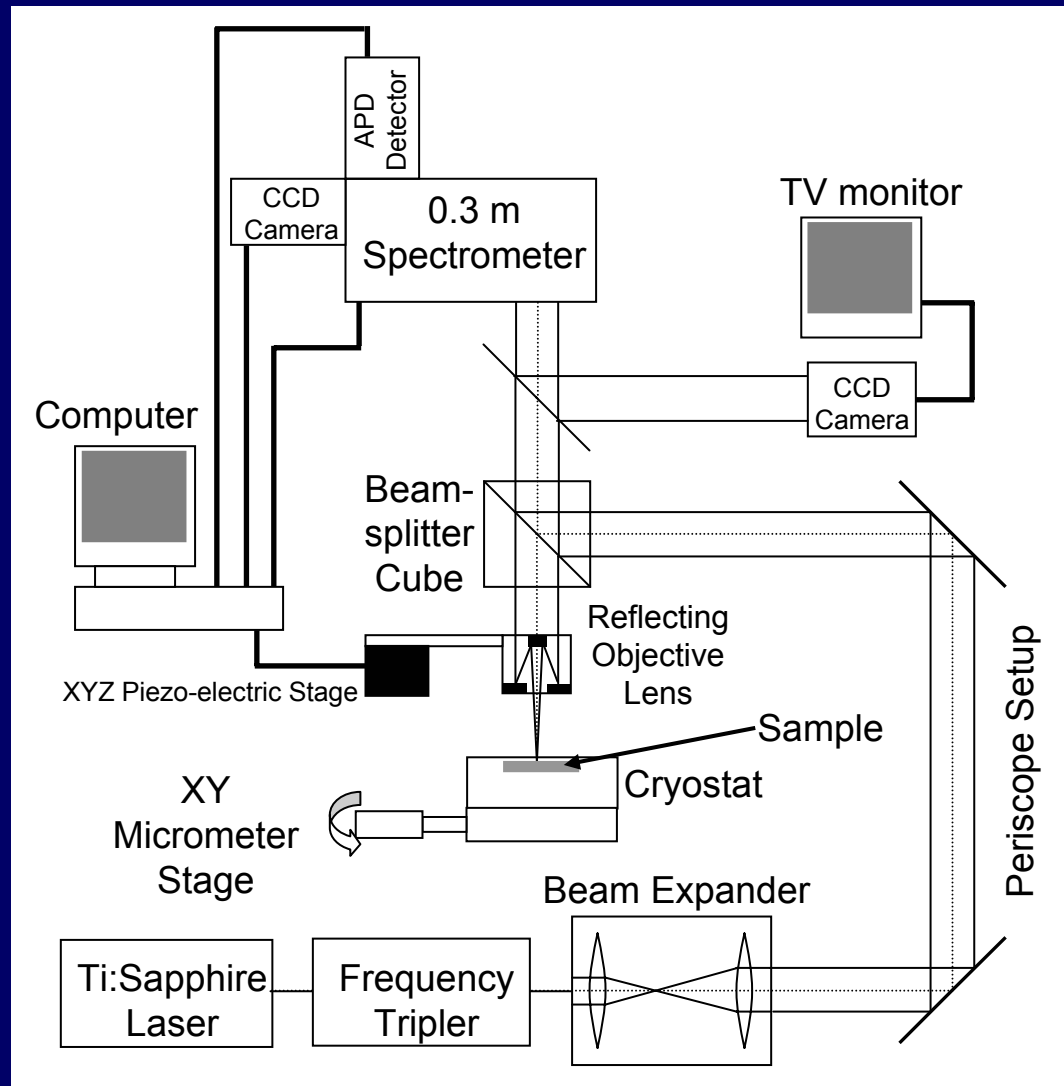
[2] R. Ram, 6.973 Semiconductor Optoelectronics lecture notes

Sample Preparation

- InGaN QD
 - Truncated-hexagonal pyramid
 - Density: $\sim 1 \times 10^{10} \text{ cm}^{-2}$
 - QD average height: $\sim 1 \text{ nm}$
 - QD base diameter: 10-20nm
- Fabricate surface metallic electrodes
 - Evaporate Al
 - 100 nm thick
 - Electron-beam lithography
 - Pattern Al electrodes
 - 1 μm gap
 - Reactive ion etching
 - SiCl_4
- Model electric field using ATLAS (Silvaco)
 - $1\text{V} = 1\text{MV/m}$

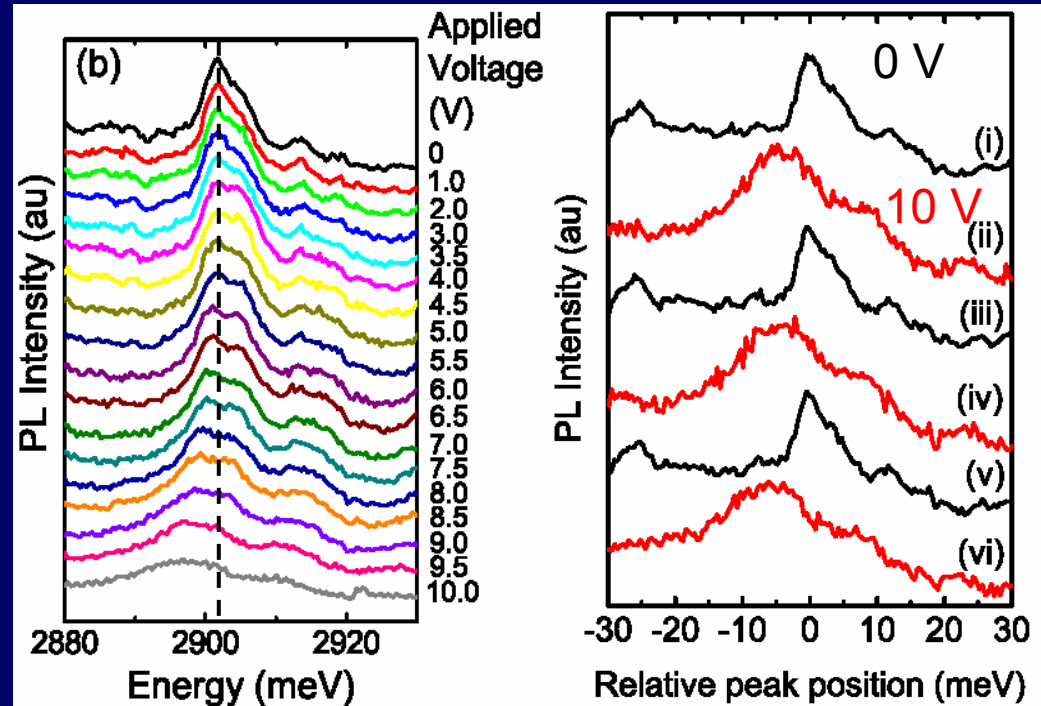


Photoluminescence (PL) Setup



Time integrated PL – Electric Field

- Exciton peak: $\sim 2.9\text{eV}$
- Apply electric field and the peak:
 - Red-shifts
 - Linewidth broadens
 - Intensity decreases
- Verified not due to heating
 - Sequential measurements
 - Same spectrum observed



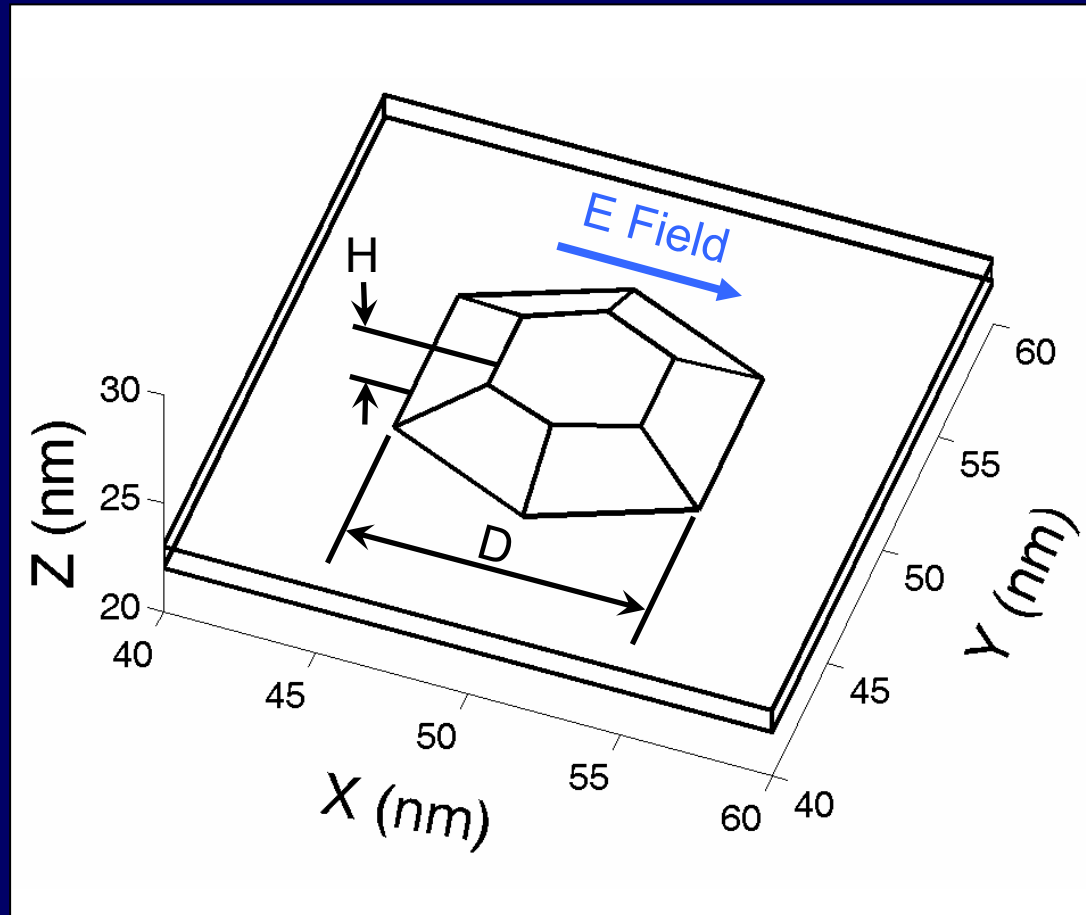
nextnano³ InGaN QD model

- 3D nanostructure simulator
- Solve self-consistent Poisson-Schrödinger equation
- Include:
 - Strain
 - Deformation potentials
 - Piezo- & pyroelectric charge
- Carriers
 - Electrons – one-band model
 - Holes – six-band **k.p** Hamiltonian
 - GaN has large bandgap
 - Neglect coupling between conduction and valence band
 - Been applied to GaN/AlN QD [3]
- Wavefunction
 - Dirichlet boundary conditions outside QD
 - Carrier confinement in QD and wetting layer (WL)

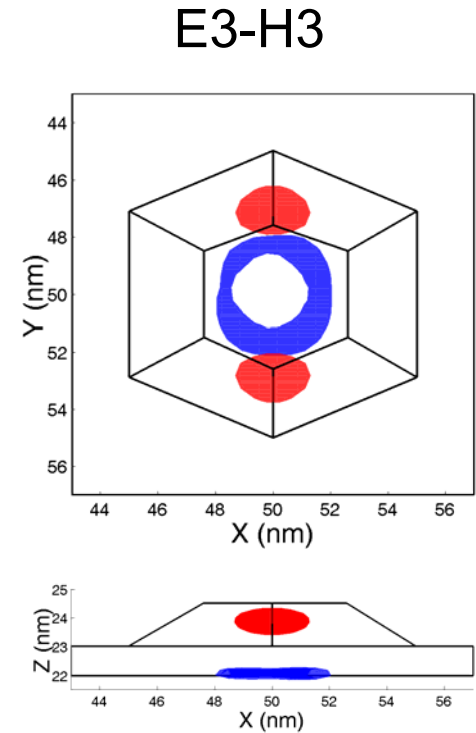
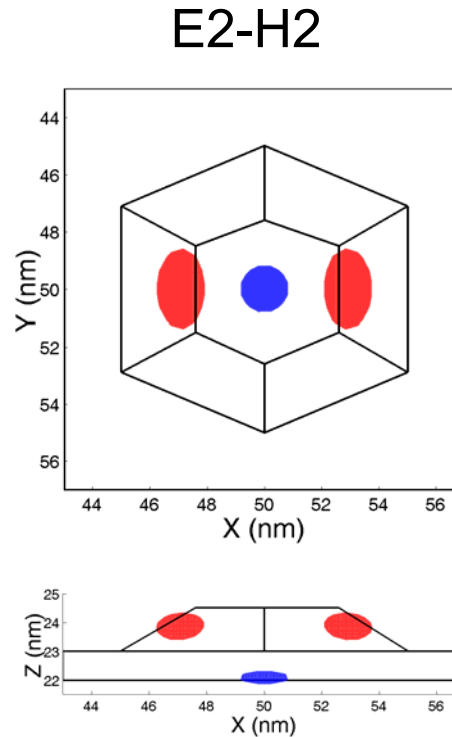
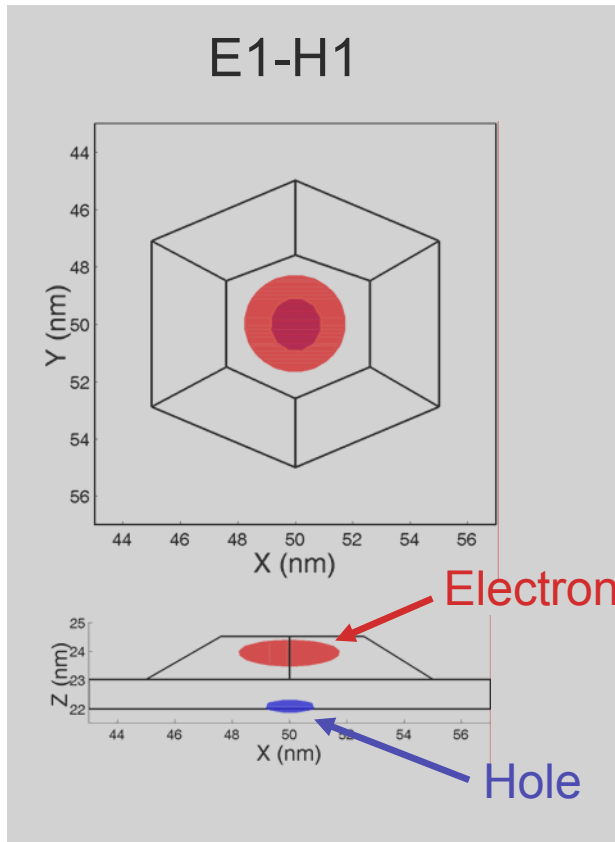
[3] V. A. Fonoberov and A. A. Balandin, JAP, 94(11), 7178, 2003

Modeling

- Structure (*modeled*)
 - WL – 1nm
 - QD height H – 1.5 nm
 - QD diameter D – 10nm
 - In content
 - ~20%
 - Uniform (WL & QD)
- Emission
 - 2.8881 eV
- Electric field along x-axis
- No compensation for Coulomb interaction
 - Future work



Electron and Hole Wavefunctions



Experimentally Observed

Effect of Lateral Electric Field

- Increase lateral electric field $\rightarrow$ QCSE
- Increases 'tilt' in band structure (lateral)
 - Electron and hole move in opposite direction

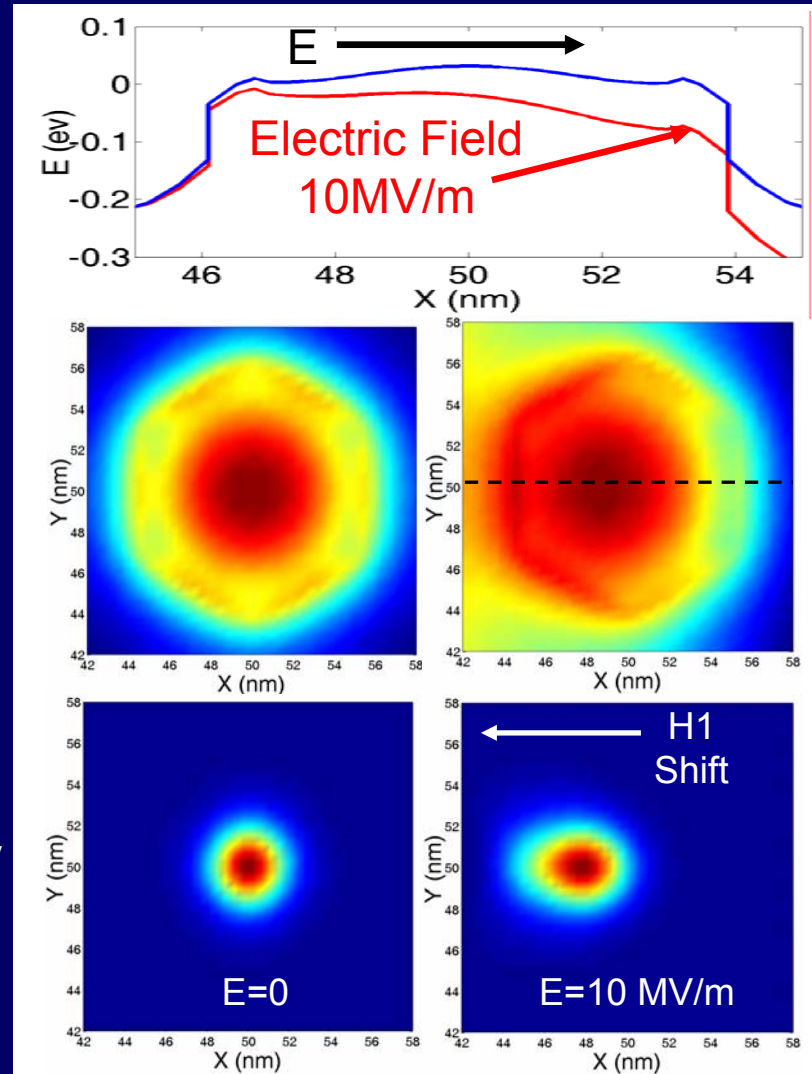
- Increased separation between electron and hole

- Decrease in overlap (oscillator strength)

$$|\langle \psi_{\text{electron}} | \psi_{\text{hole}} \rangle|^2$$

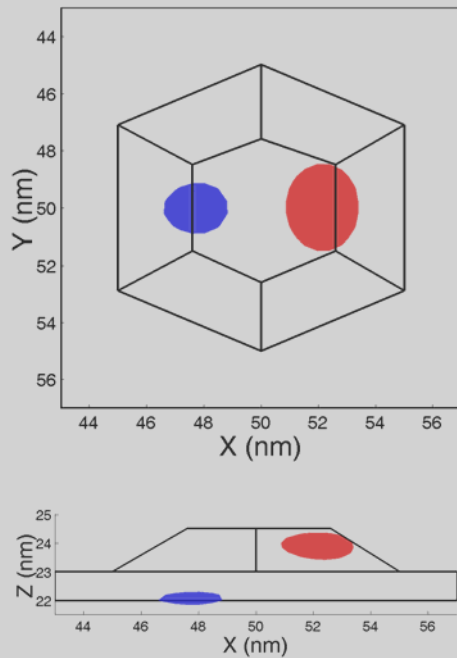
Valence Band
Z=22.5nm

H1
Probability Density



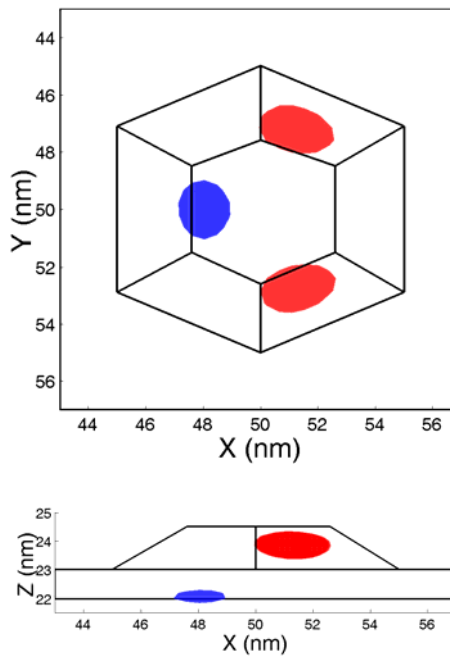
Effect of Lateral Electric Field

E1-H1

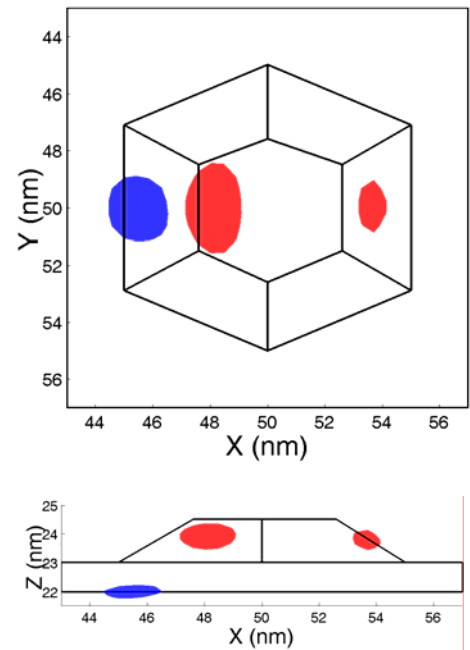


$E = 10\text{MV/m} \rightarrow$

E2-H2

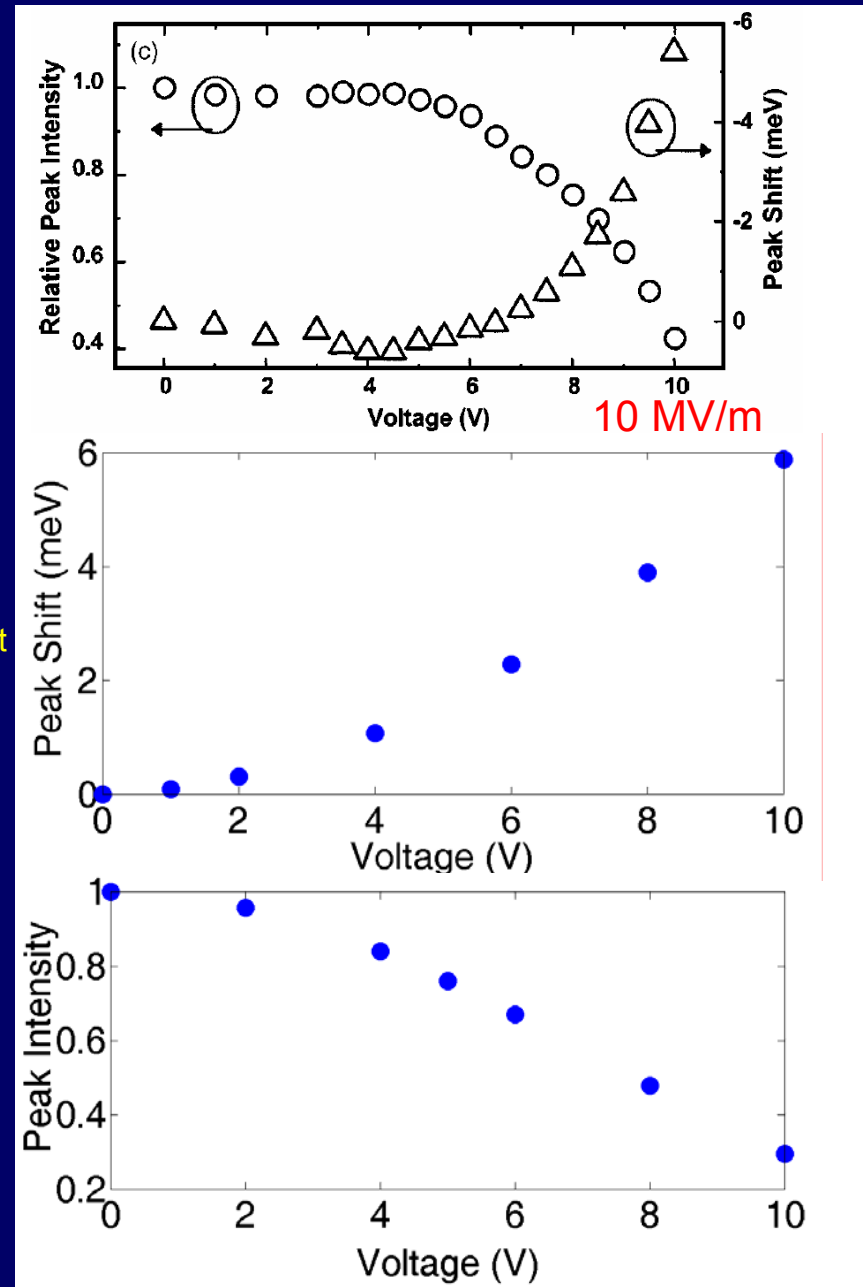


E3-H3



Comparison with Experiment

- Red-shift
 - Measured: ~6 meV
 - Simulated: 6 meV
- Peak decrease
 - Measured: 40%
 - Simulated: 30%
- Peak shift $E(F)$:
 - $E(F) = \mu F - \alpha F^2$
 - Permanent dipole moment
 - $\mu = 1 \times 10^{-29}$ Cm
 - $\alpha = 1 \times 10^{-35}$ Jm²V⁻²
 - Polarizability
- Non zero μ
 - Indicates that the lateral permanent dipole moment is significant
 - Used 'standard' nextnano³ parameters (Vurgaftman)
 - Supports correctness of parameters
- **Good agreement between modeling and experiment !**



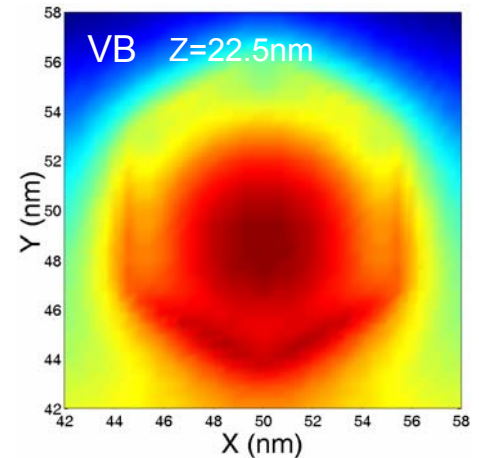
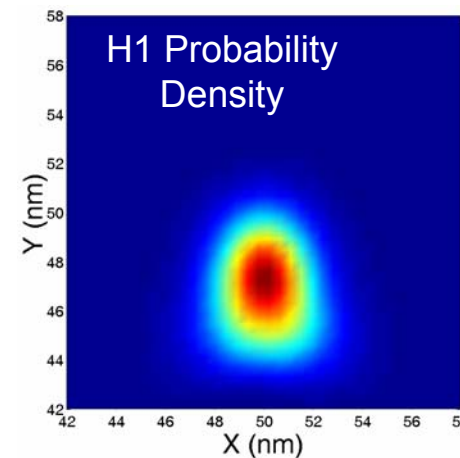
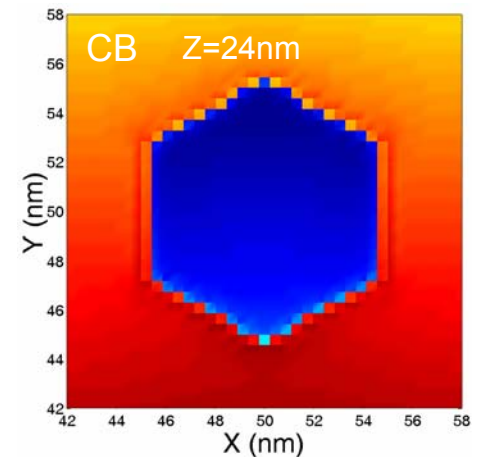
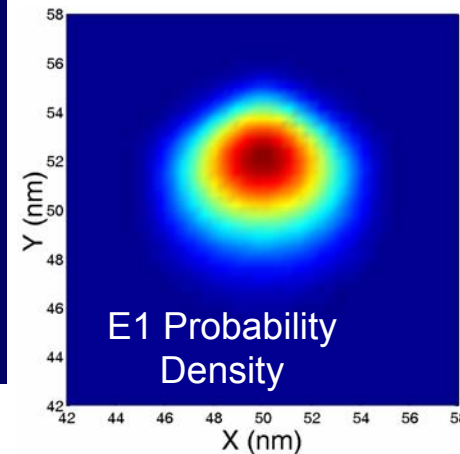
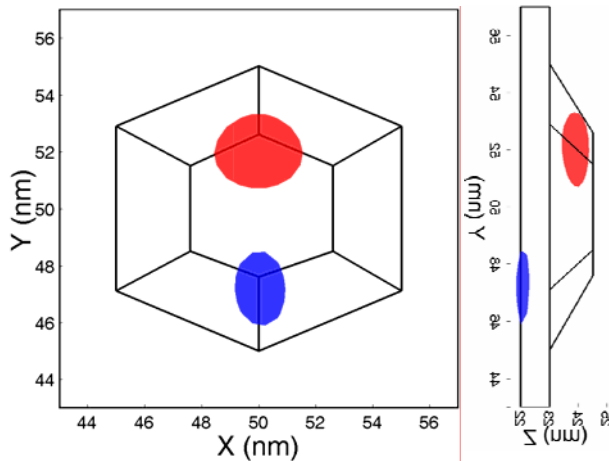
[4] J.W. Robinson, et al, APL 86 213103, 2005

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Unanswered Questions...

- Effect of QD parameters (composition, H, D) on QCSE
- Effect of electric field orientation
 - In this study, simplify by assuming E field aligned to QD axis
 - Experimentally, this may not be the case...
 - Misalignment between QD growth direction and electrode location
 - Electric field pattern
 - How does this affect the QCSE ?
 - Electric field in Y direction – PL shift ~ same

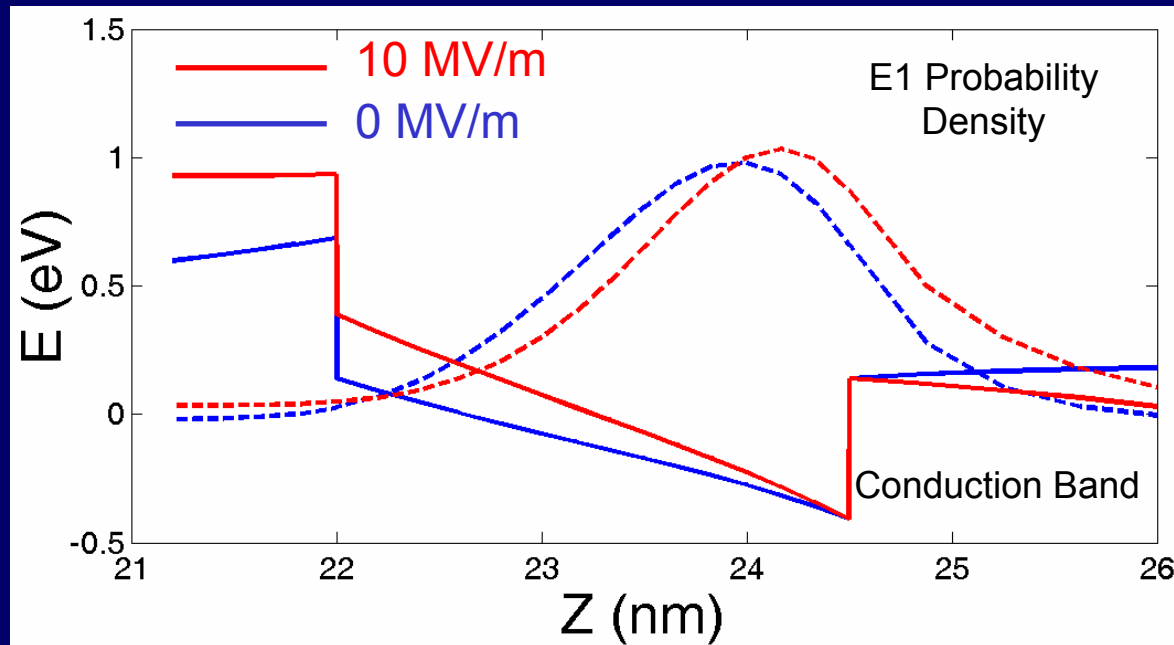
E1-H1



$E=10 \text{ MV/m}$

Effect of Vertical Electric Field

- Preliminary result
- Shift approximately linear:
 - 0.5 meV shift per MV/m
 - Agrees well with observations (GaN/AlN QD)
- Important for CQED
 - Allows tuning (blue & red shift) of the emitter mode
 - Allows emitter mode to be in resonance with the cavity mode



Conclusion

- InGaN QD modeled using nextnano³
- Provided insight into effect of laterally applied electric field in InGaN QD
 - Explains the observation from earlier studies
 - Lateral permanent dipole moment is significant
- Application in QIP – tuning QD modes in cavity quantum electrodynamics
- **Future work** – Understand how the QD parameters (composition, H, D) and E field orientation affect QCSE

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