



The impact of the wetting layer on the optoelectronic properties of a quantum dash material

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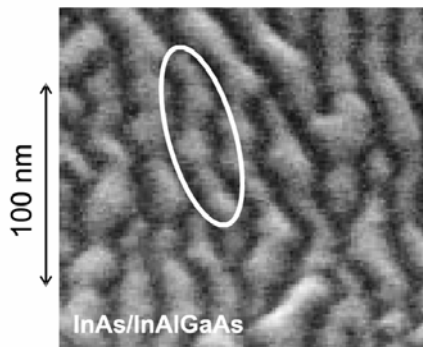
Outline

- Introduction:
 - peculiar characteristics of the QDash material
 - goal of the work
- Numerical model for the calculation of the optoelectronic properties
- Simulation results
- Conclusions

Introduction (1)

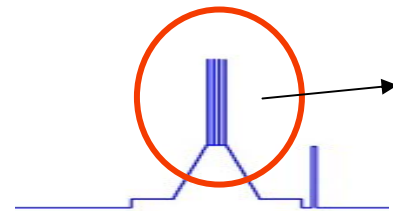
The InAs/InP QDash material grown at the University of Wurzburg (Germany) under the BigBand project

QDash: elongated InAs islands grown on InAlGaAs/InP substrate



Active waveguide for applications requiring wide optical gain bandwidth

- External cavity tunable lasers
- Broad band SOA



4 QDash layers separated by 25 nm $\text{In}_{0.528}\text{Al}_{0.238}\text{Ga}_{0.234}\text{As}$ spacer ("barrier")

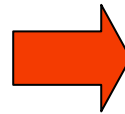
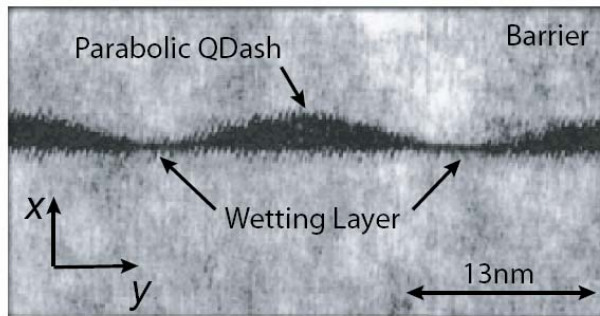
Material characteristics

- QWire nature of the ensemble
- High dash density
- Large fluctuations of the dash size => inhomogeneous broadening => wide optical gain spectrum

Introduction (2)

QDash transversal cross section

TEM image



- Dashes with a semi-parabolic cross section
- Presence of the InAs WL film
- Dash separation smaller than the dash width due to high density

The purpose of the modeling work:

- calculation of the CB and VB states of the QDash ensemble
- calculation of the gain characteristics (spectrum, dg/dN , optical gain bandwidth ...)
- design of an improved QDash material for wide gain bandwidth

- Including the WL and the quantum mechanical coupling among adjacent dashes
- Comparing the results with the single isolated dash case

Numerical model (1)

1 Solution of the single particle Schrodinger equation in the effective mass approximation => CB and VB confined and unconfined states



2 Calculation of the density of states in CB and VB



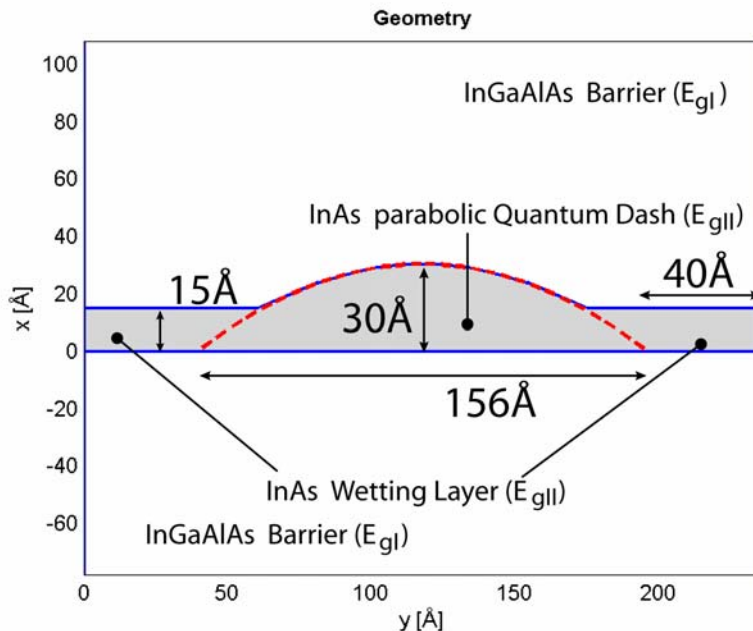
3 Calculation of the occupation probabilities => quasi-Fermi level imposing neutrality condition per layer



4 Calculation of the gain spectra

Numerical model (2)

Calculation of CB and VB confined and unconfined states



- Solution of the single particle Schrodinger equation using FemLAB

- **Case with dash coupling:**

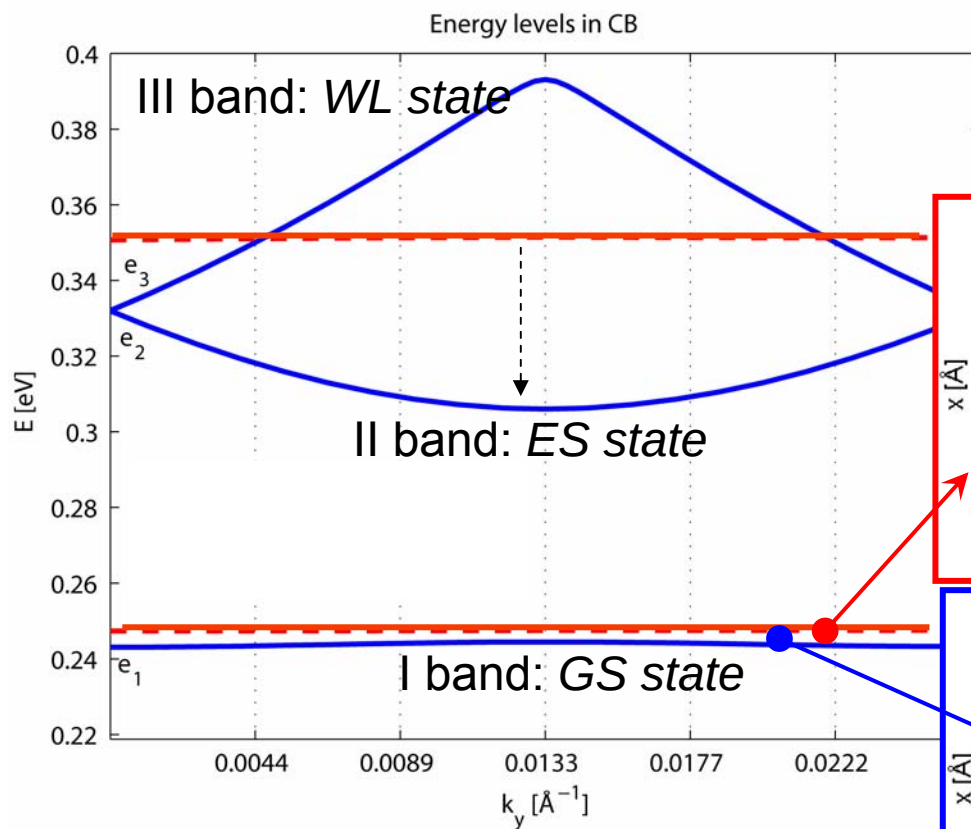
- wavefunction: $\frac{1}{L} u(x, y) \cdot e^{-jk_y y} \cdot e^{-jk_z z}$
- periodic boundary condition

- **Single isolated dash:**

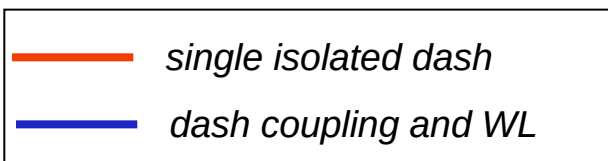
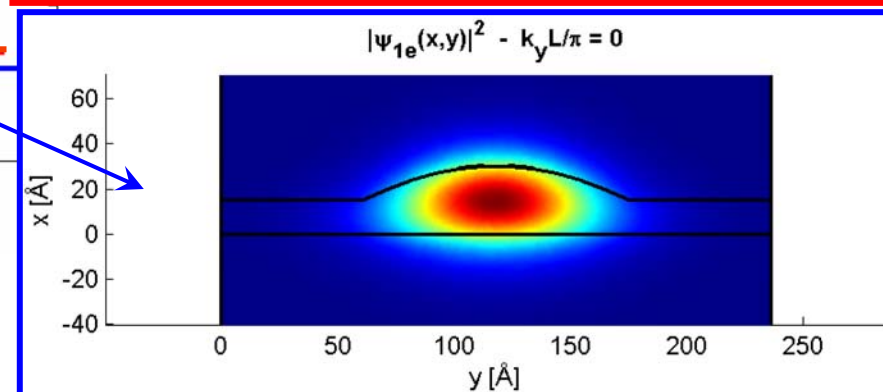
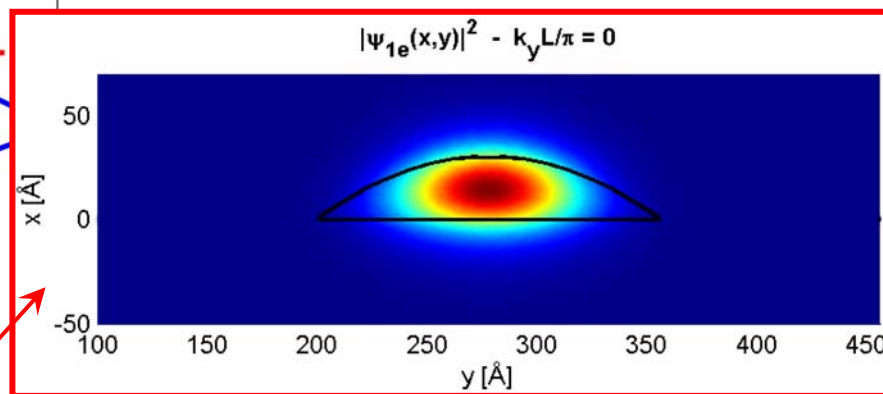
- wavefunction: $\psi(x, y) \cdot e^{-jk_z z}$
- Dirichelet boundary conditions in a large box

Numerical model (3)

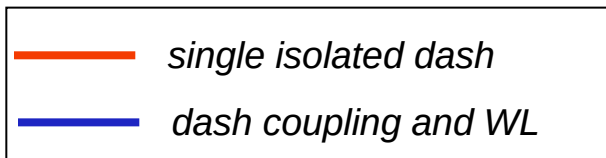
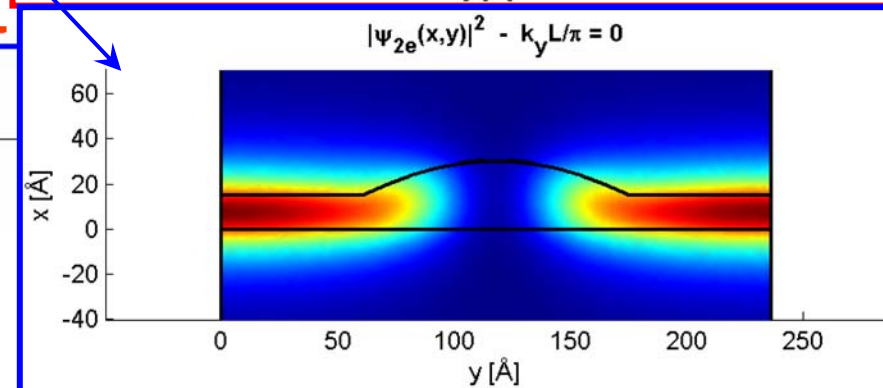
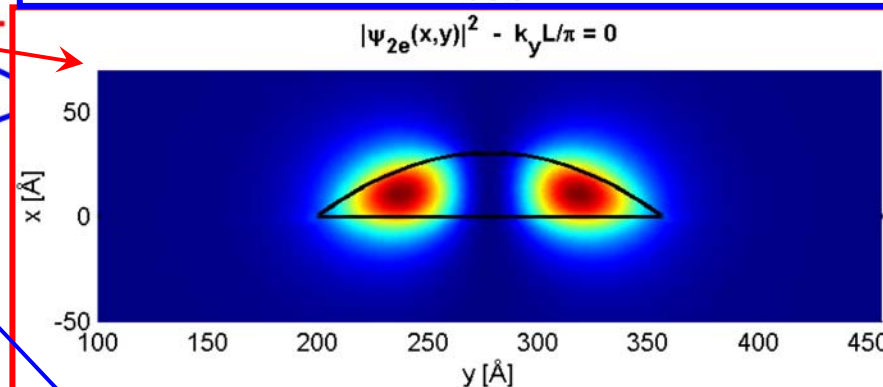
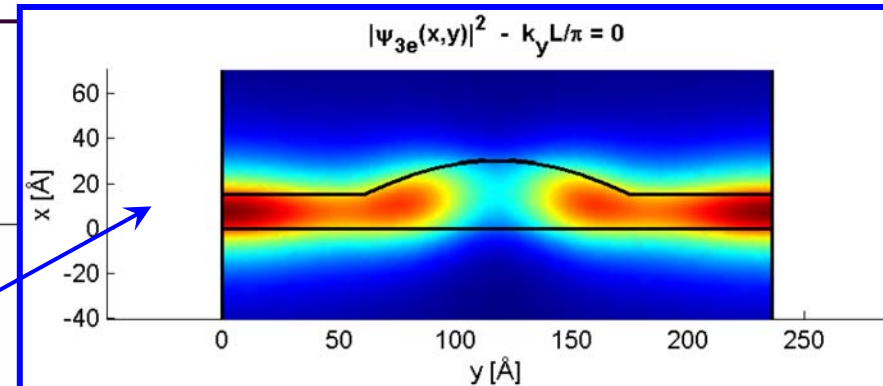
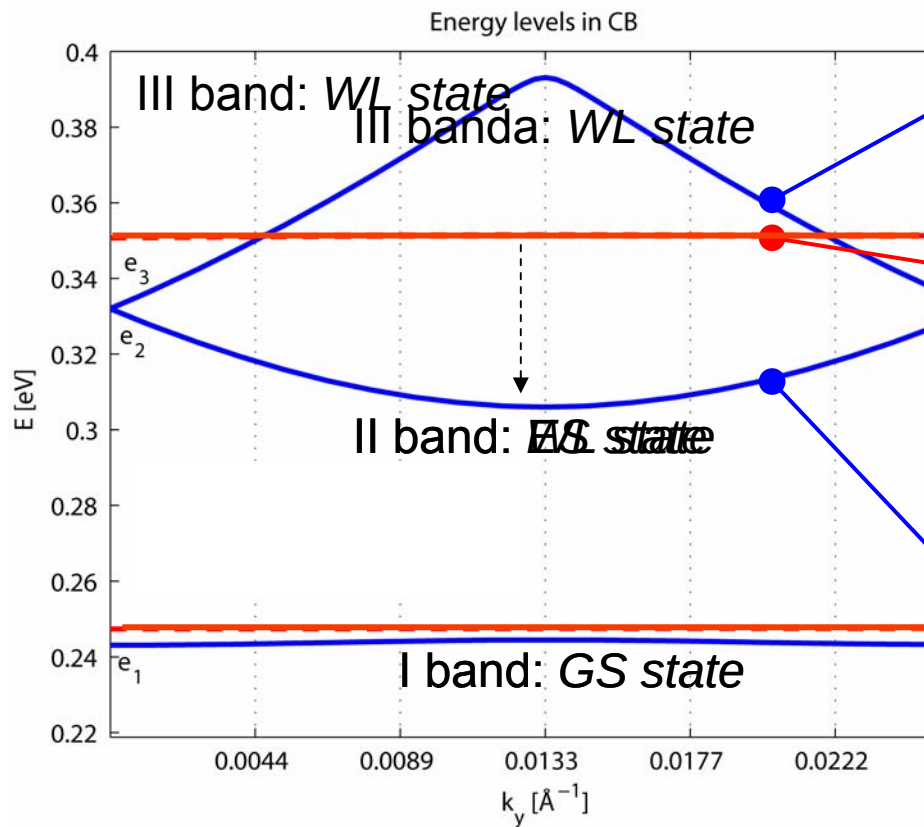
Conduction band energy diagram



GS wavefunction

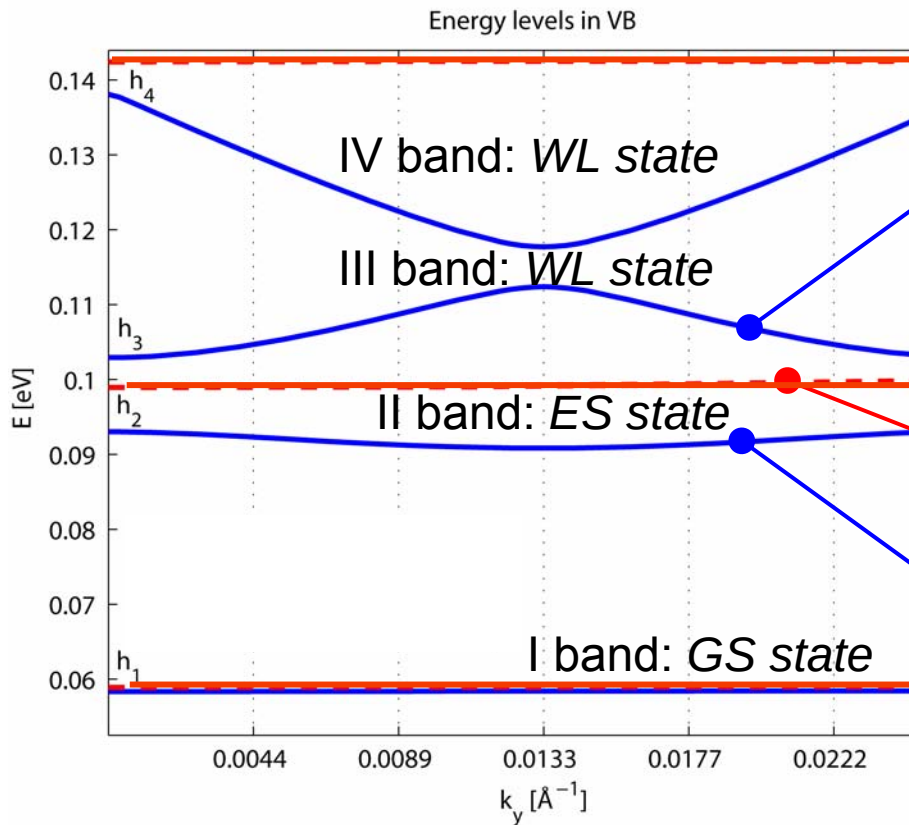


Numerical model (3)

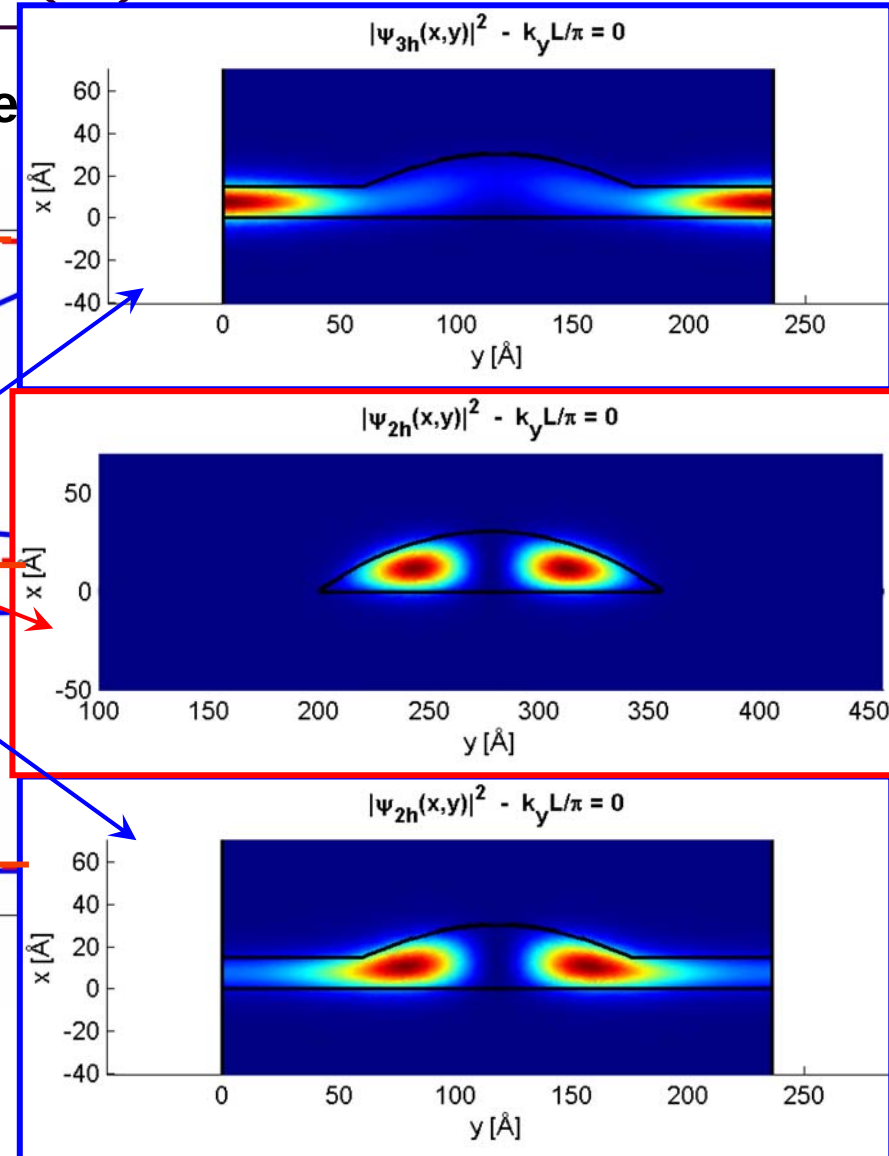


Numerical model (4)

Valence band e

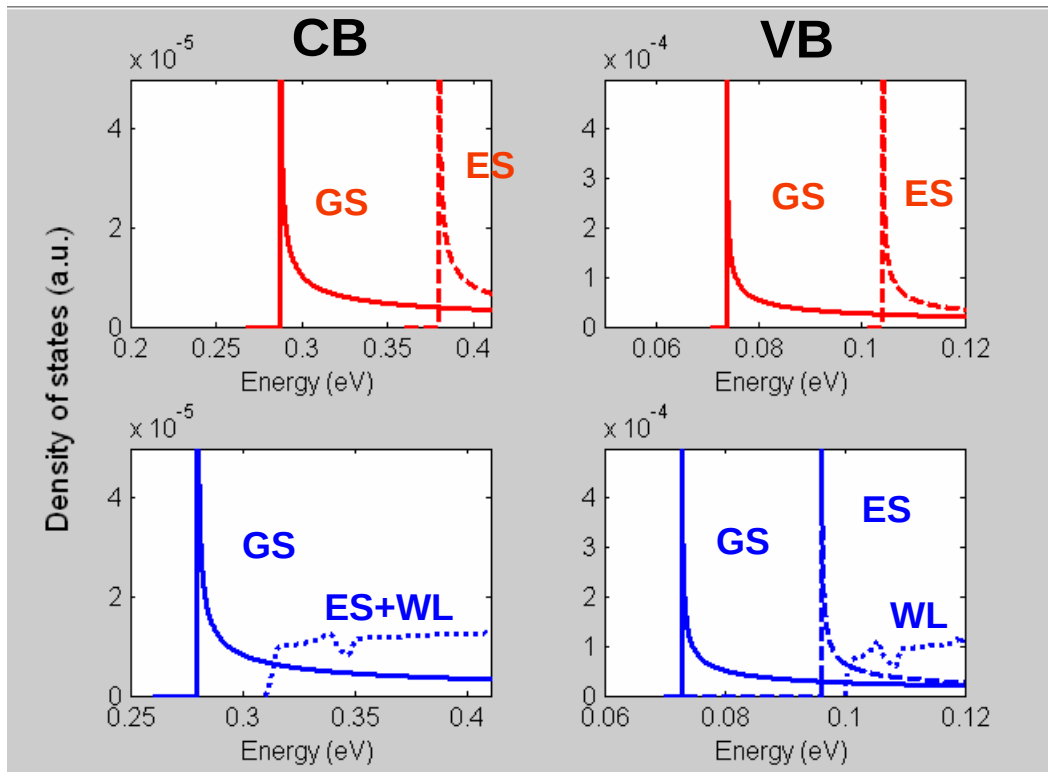


- single isolated dash
- dash coupling and WL



Numerical model (5)

Numerical calculation of the density of states from the CB and VB energy diagram



Single isolated dash:
typical QWire DOS

Dash coupling and WL:

- in CB the ES+WL gives a step-like DOS (2D state)
- in VB the ES DOS has still a QWire nature, the step-like DOS is only due to the WL

Numerical model (6)

Calculation of the gain spectra

$$g_{net}(\lambda) = \Gamma_{active} [g_{GS_{conf,conf}}(\lambda) + \underbrace{g_{ES_{unconf,conf}}(\lambda) + g_{WL}(\lambda)}_{\underbrace{g_{ES_{conf,conf}}(\lambda)}}] - \alpha_i - \Gamma_{barrier}\alpha_{barrier}$$

Recombination between confined states: $g_{GS,ES_{conf,conf}}$

$$g_{GS,ES_{conf,conf}} = \frac{C_g}{\hbar\omega} \cdot \sum_{j=1}^{N_{wire}} P_{wire,j} \int M_b^2 I_{jconf,conf}^2 \rho_{wire,j}(\varepsilon) [f_e(\varepsilon_e) + f_h(\varepsilon_h) - 1] L(\hbar\omega - \varepsilon) d\varepsilon$$

QDash size fluctuation:
inhomogeneous broadening of the gain
spectrum

Qwire reduced density of states

Numerical model (6)

Calculation of the gain spectra

$$g_{net}(\lambda) = \Gamma_{active} [g_{GS_{conf,conf}}(\lambda) + \underbrace{g_{ES_{unconf,conf}}(\lambda)}_{\substack{g_{ES} \\ conf,conf}}(\lambda) + g_{WL}(\lambda)] - \alpha_i - \Gamma_{barrier}\alpha_{barrier}$$

Recombination between unconfined states in CB and confined states in VB

$g_{ESunconf,conf}$

$$g_{unconf,conf}(\hbar\omega) = \frac{C_g}{\hbar\omega} \int \int_{k_y, k_z} \frac{L}{2\pi^2 A} M_b^2 I_{unconf,conf}^2(k_y) \cdot [f_e(\varepsilon_e) + f_h(\varepsilon_h) - 1] L(\hbar\omega - \varepsilon) dk_y dk_z$$

Sum of all the contribution from the ES mini-band in CB

Overlap integral between the envelope function of the CB unconf. ES in CB and conf. ES in VB: $I_{unconf,conf}^2 \ll I_{conf,conf}^2$

Numerical model (6)

Calculation of the gain spectra

$$g_{net}(\lambda) = \Gamma_{active} \left[g_{GS_{conf,conf}}(\lambda) + \left\{ \begin{array}{l} \underline{g_{ES_{unconf,conf}}(\lambda)} + \textcircled{g_{WL}(\lambda)} \\ \underline{g_{ES_{conf,conf}}(\lambda)} \end{array} \right\} \right] - \alpha_i - \Gamma_{barrier} \alpha_{barrier}$$

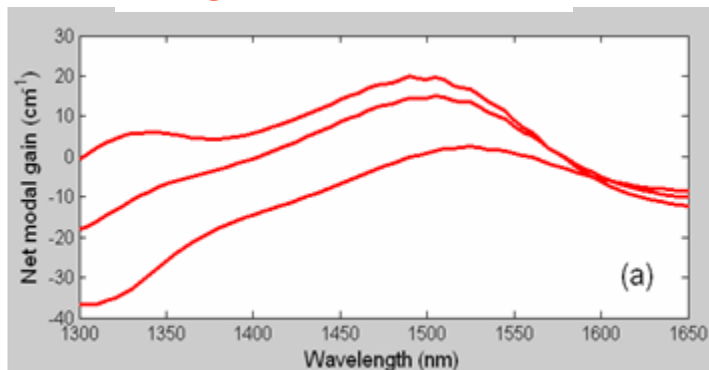
Recombination between WL states

$$g_{WL} = \frac{C_g}{\hbar\omega} \cdot \int M_b^2 I_{WL}^2 \textcircled{\rho_{WL}(\varepsilon)} [f_e(\varepsilon_e) + f_h(\varepsilon_h) - 1] L(\hbar\omega - \varepsilon) d\varepsilon$$

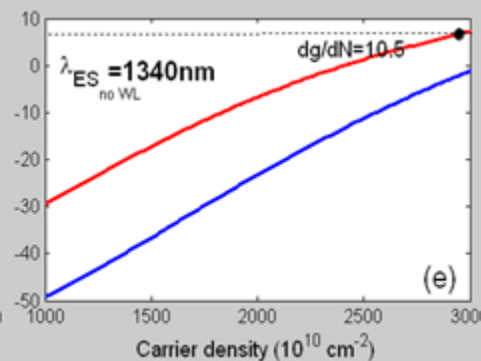
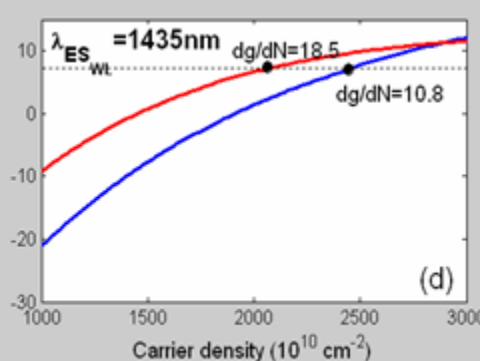
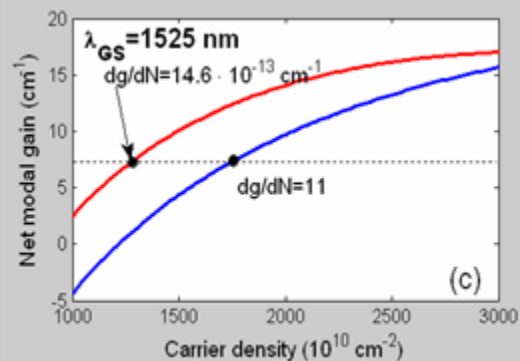
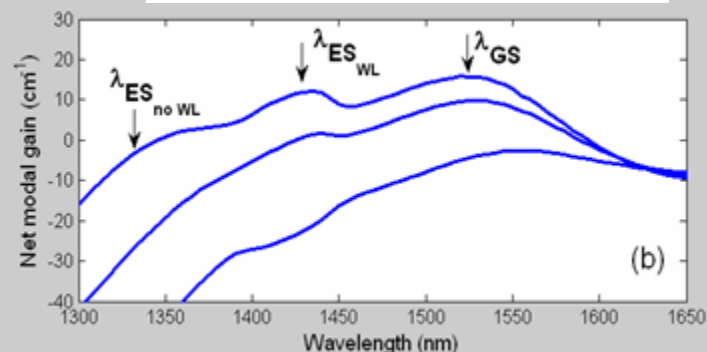
2D reduced density of states

Gain performance

Single isolated dash



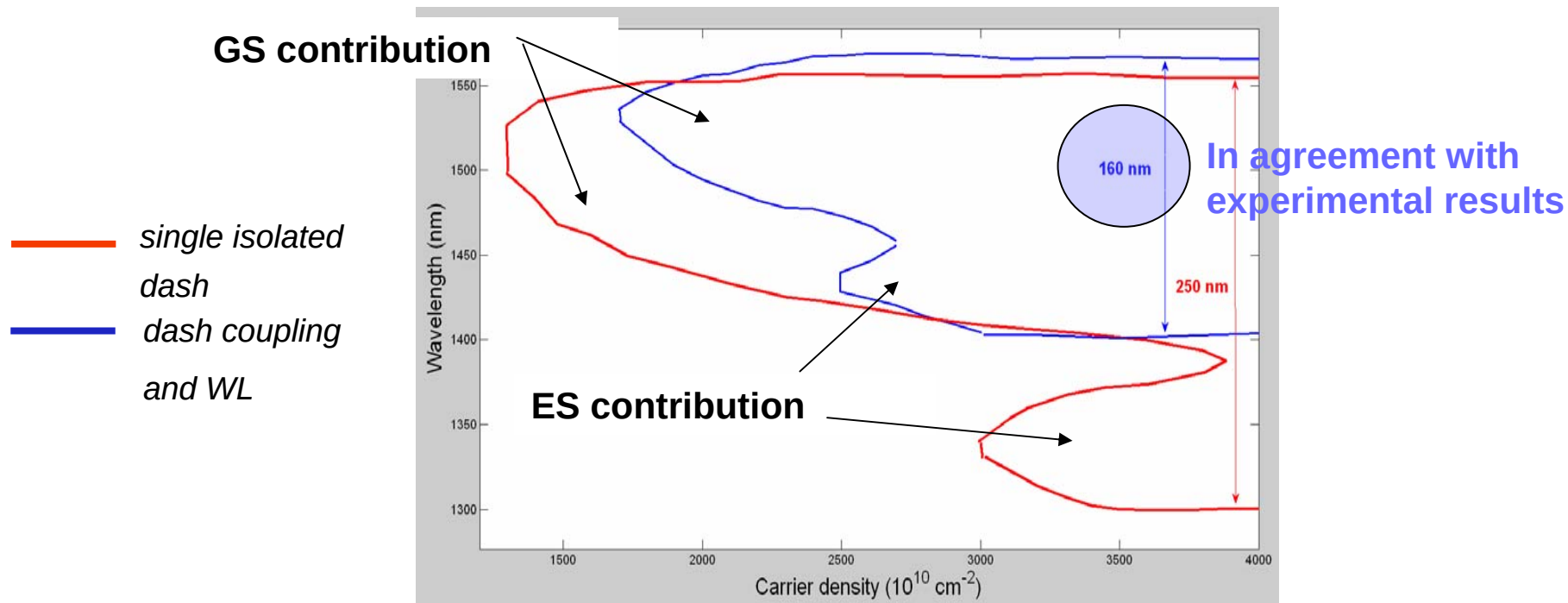
Dash coupling and WL



The presence of the WL and the dash coupling limits the maximum gain and the differential gain

Optical gain bandwidth

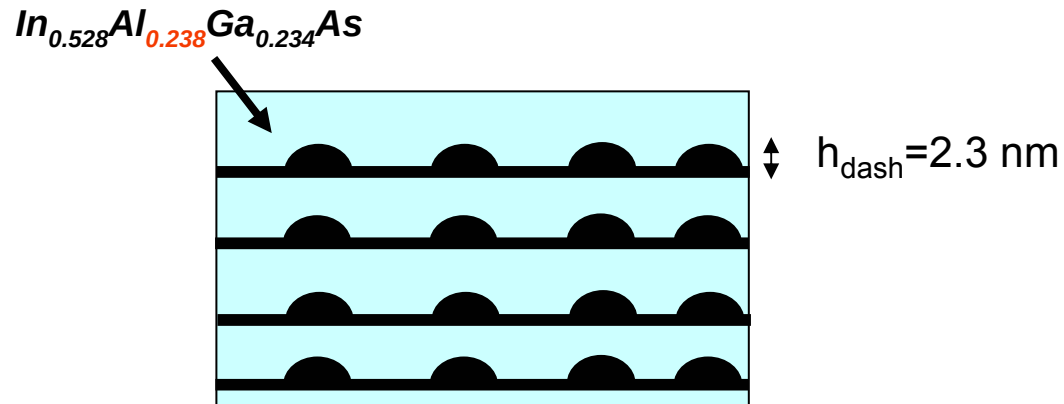
Wavelength range where $g(\lambda) > g_{th} = 7 \text{ cm}^{-1}$



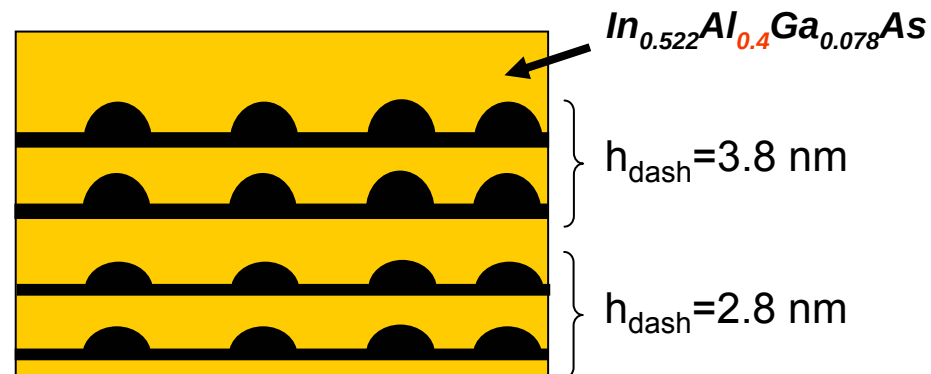
The presence of the WL and the high dash density (coupling) reduces the maximum optical gain bandwidth

Improved QDash material

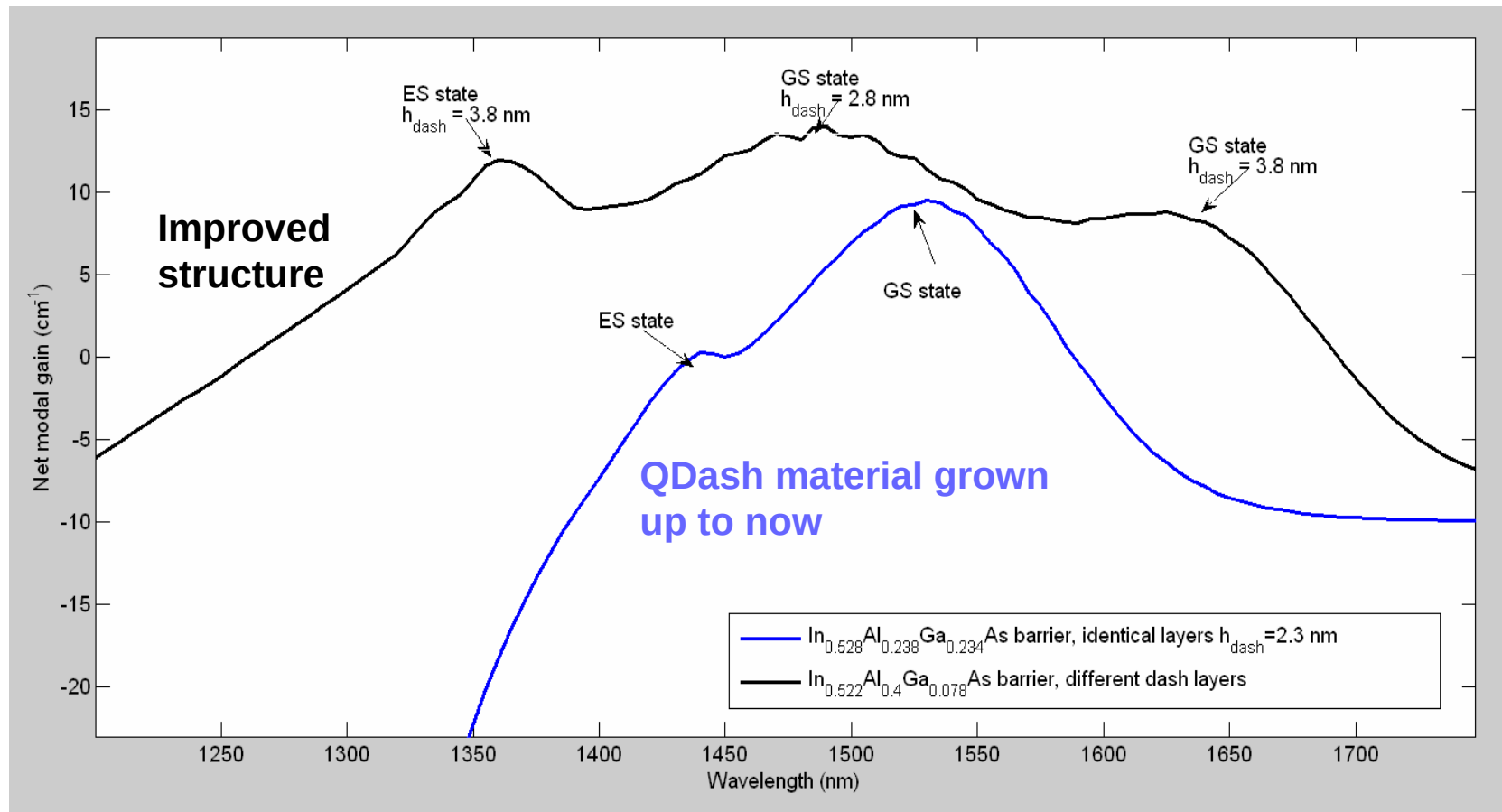
Standard QDash structure



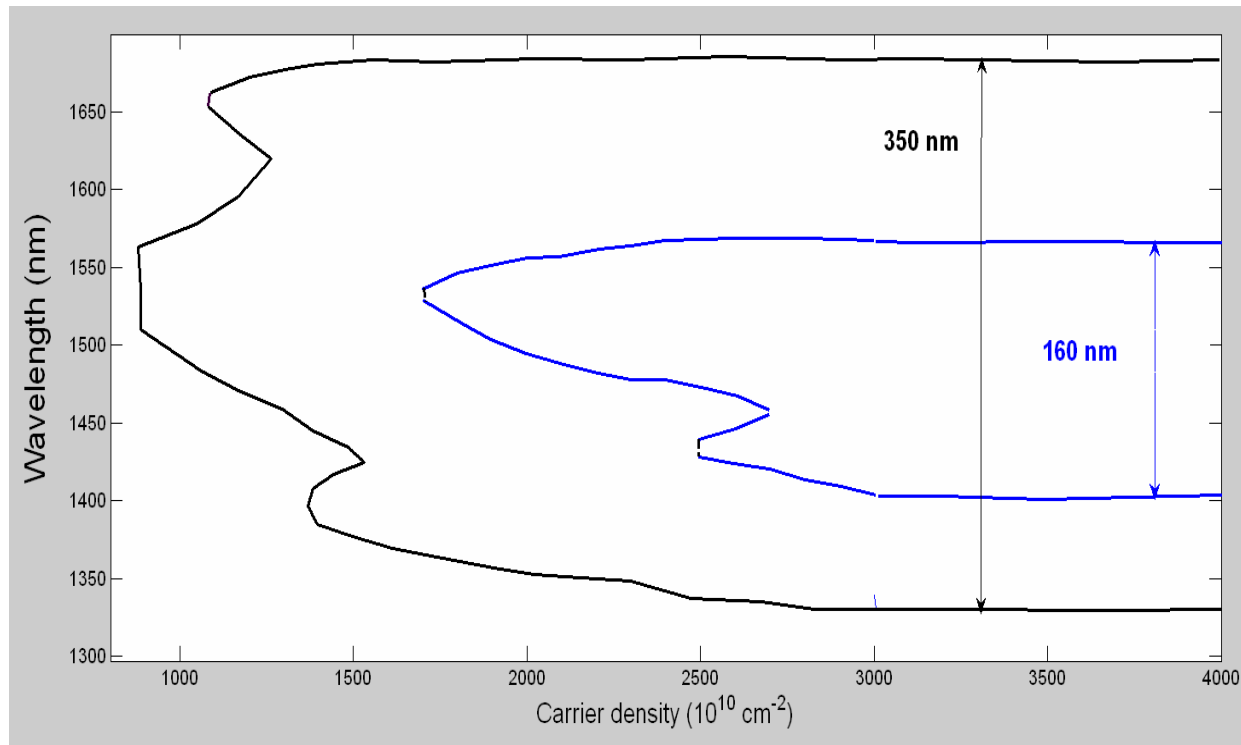
New design



Comparison of gain spectra



Extended optical gain bandwidth



A very wide bandwidth is obtained also at lower carrier injection, thanks to the improved confinement of electrons and holes in the dashes

Conclusions

- We have presented a self-consistent numerical model for the calculation of the optoelectronic characteristics of a realistic InAs/InP QDash material
- The model takes into account the presence of the WL and the quantum mechanical coupling among adjacent dashes
- It shows that the WL and high dash density can limit the gain performance and in particular the maximum optical gain bandwidth
- The model have been used to propose a new QDash structure that overcomes these limitations by increasing the Al concentration of the spacer and using dash layers of different thickness

