

Section 6

Electron Tunneling - Emergence of Bandstructure

6.4 Tunneling through N barriers

Gerhard Klimeck
gekco@purdue.edu

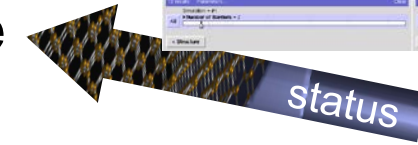
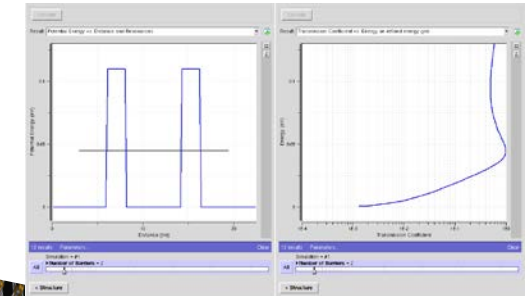
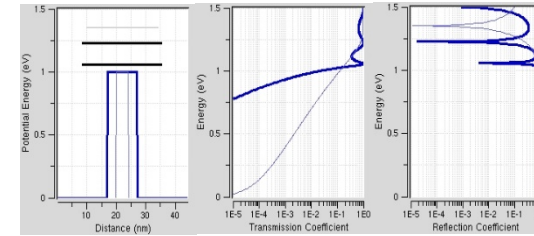
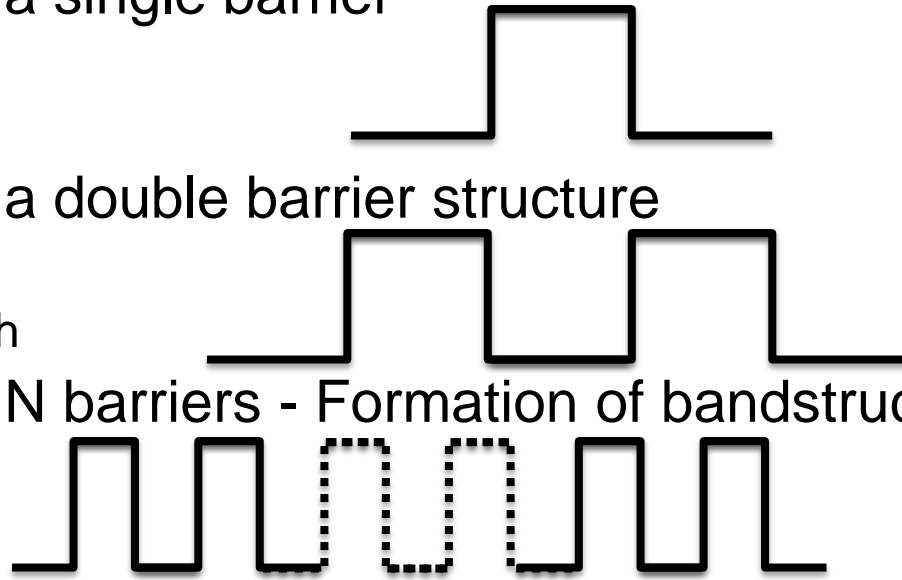


School of Electrical and
Computer Engineering

Section 6

Electron Tunneling - Emergence of Bandstructure

- 6.1 Transfer Matrix Method
- 6.2 Tunneling through a single barrier
 - » Analytical Solution
 - » Numerical observations
- 6.3 Tunneling through a double barrier structure
 - » Resonant Transmission
 - » Transmission Peak Width
- 6.4 Tunneling through N barriers - Formation of bandstructure
- 6.5 Analytical and Numerical Solution Strategies



Reference:

piece-wise-constant-potential-barrier tool <http://nanohub.org/tools/pcpbt>

Section 6

Electron Tunneling - Emergence of Bandstructure

Video

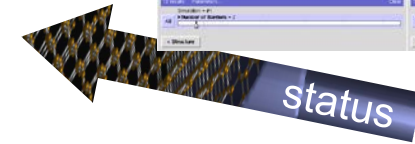
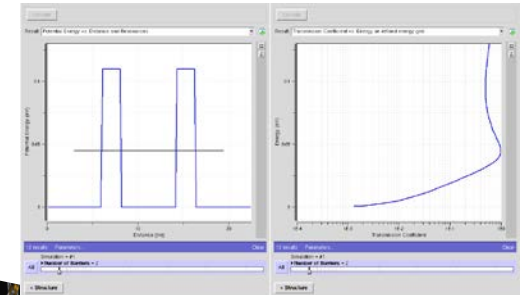
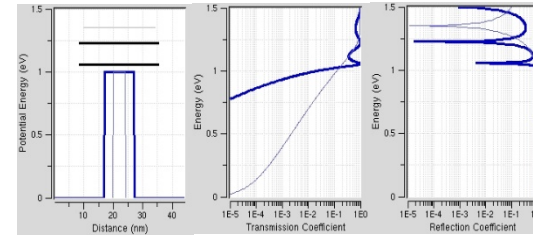
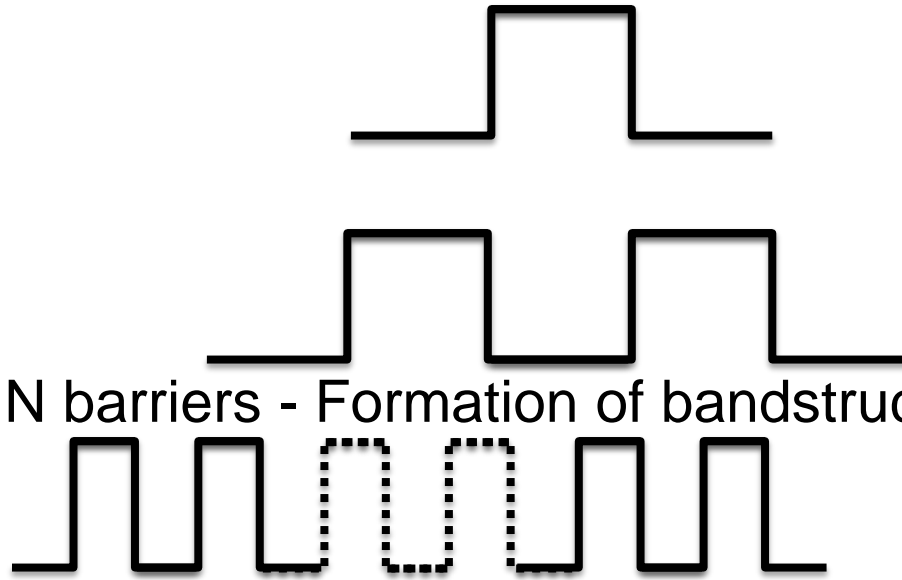
Video Segment

Video Segment

Video Segment

Video Segment

- 6.4 Tunneling through N barriers - Formation of bandstructure

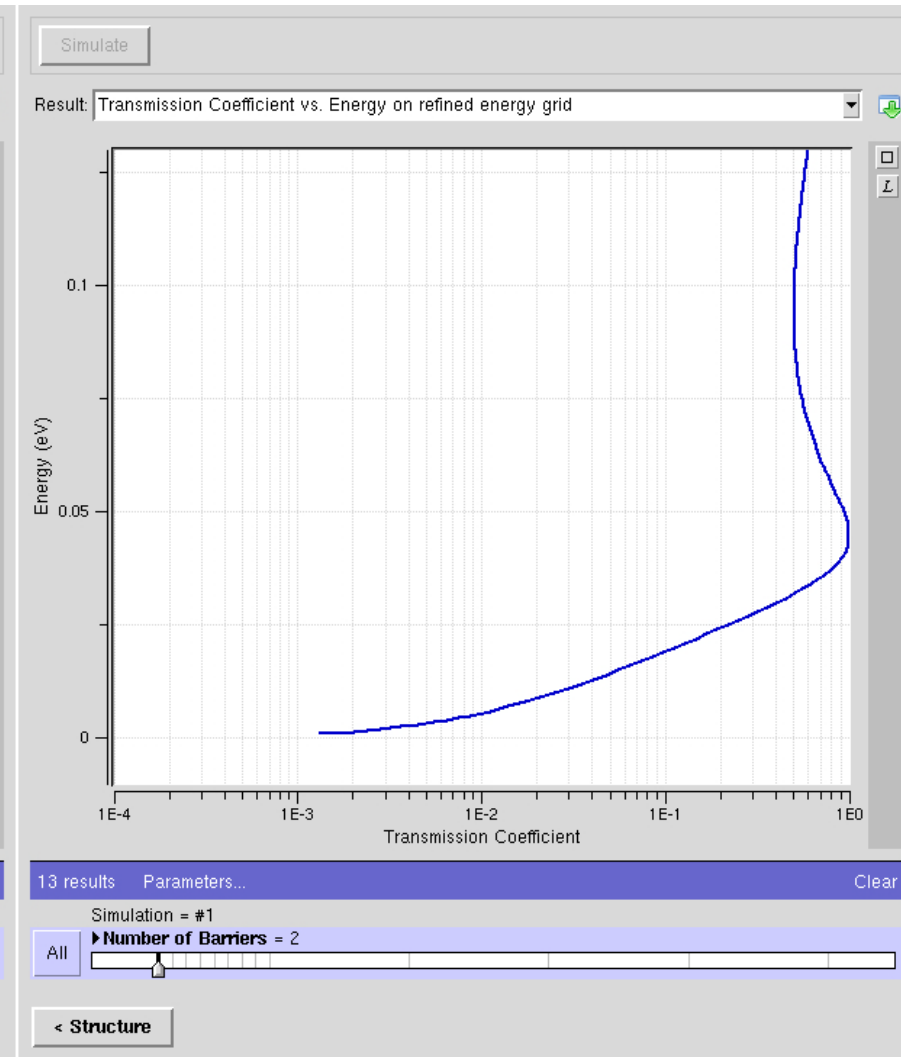
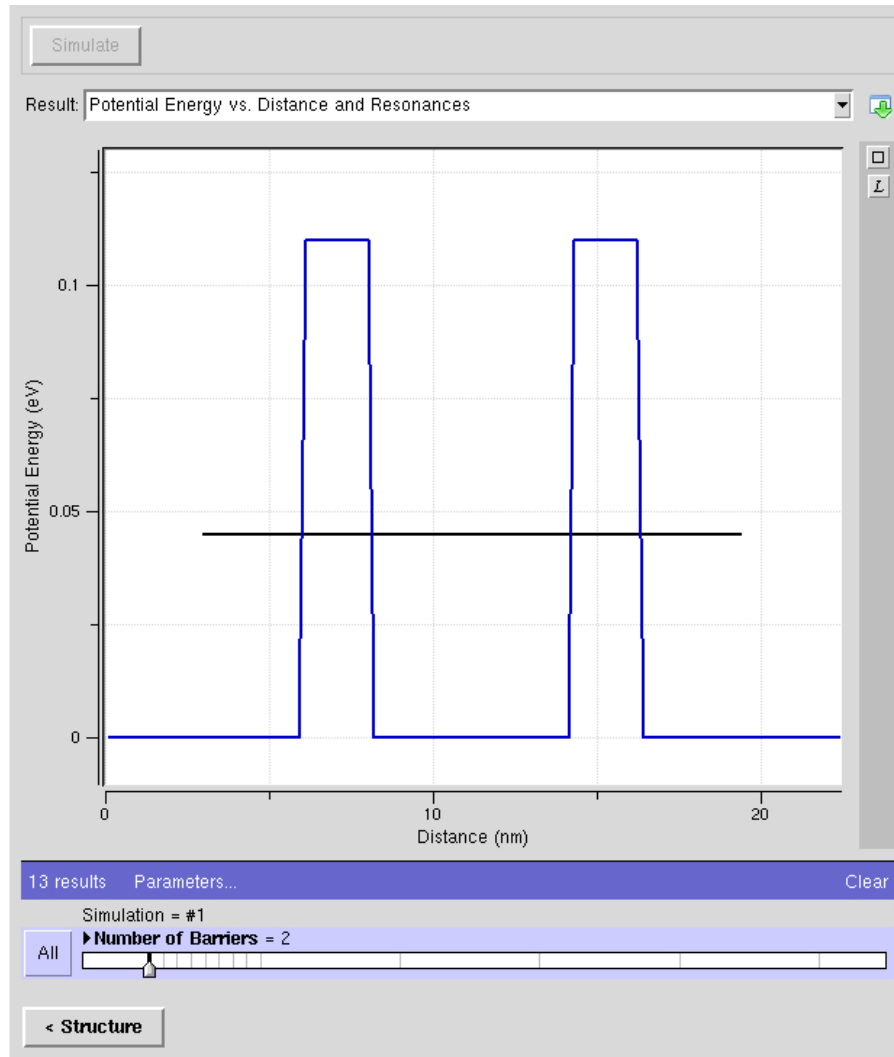


status

Reference:

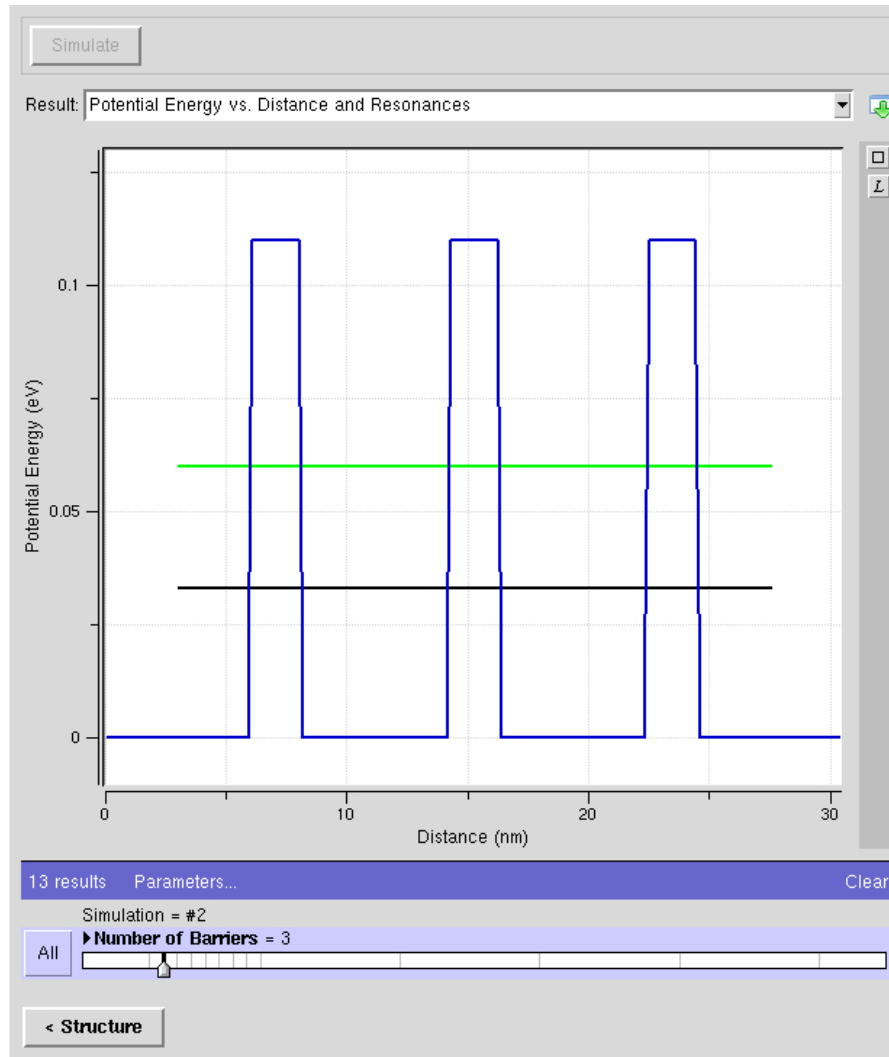
piece-wise-constant-potential-barrier tool <http://nanohub.org/tools/pcpbt>

1 Well => 1 Transmission Peak

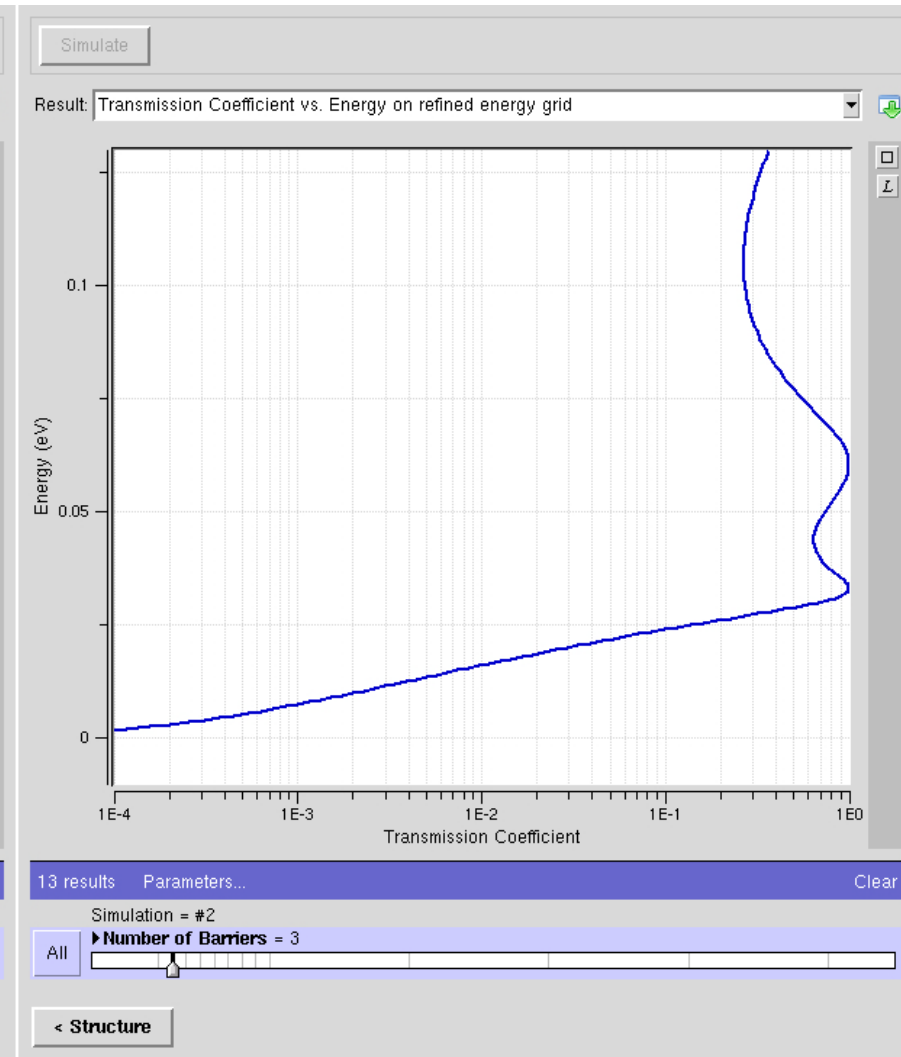


- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

2 Wells => 2 Transmission Peaks

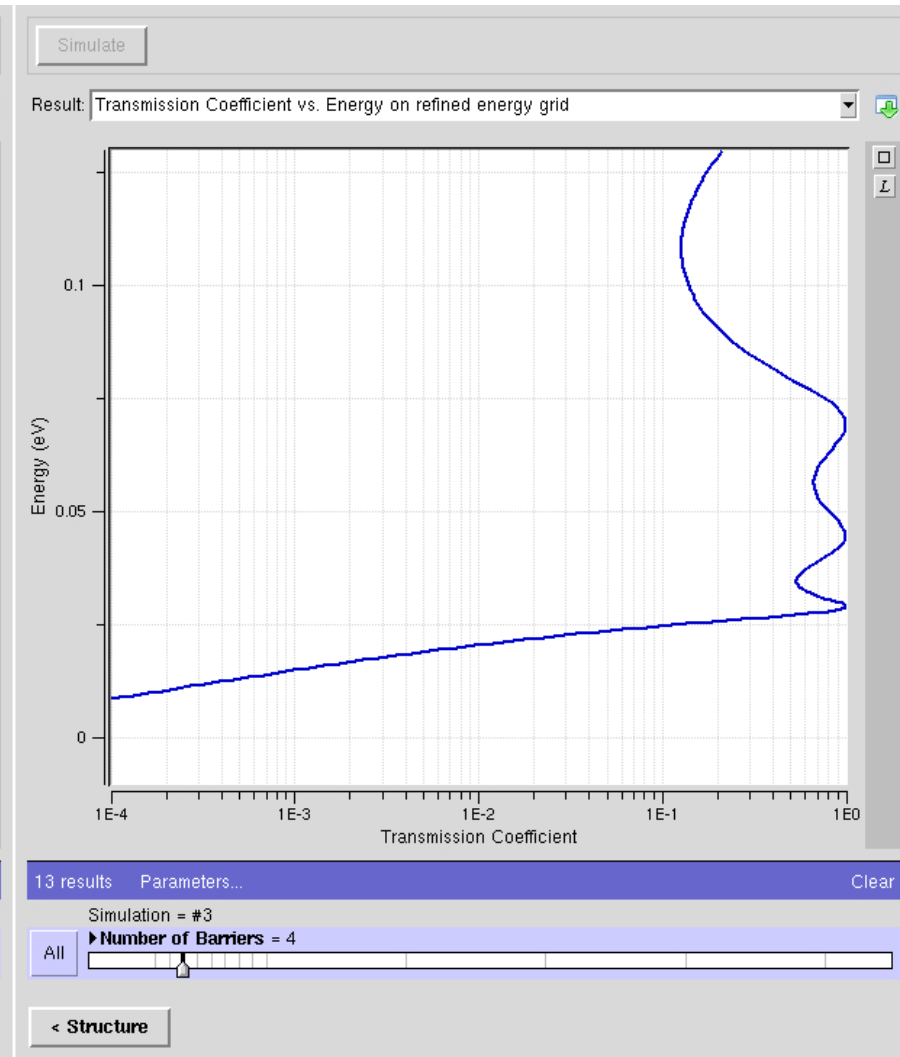
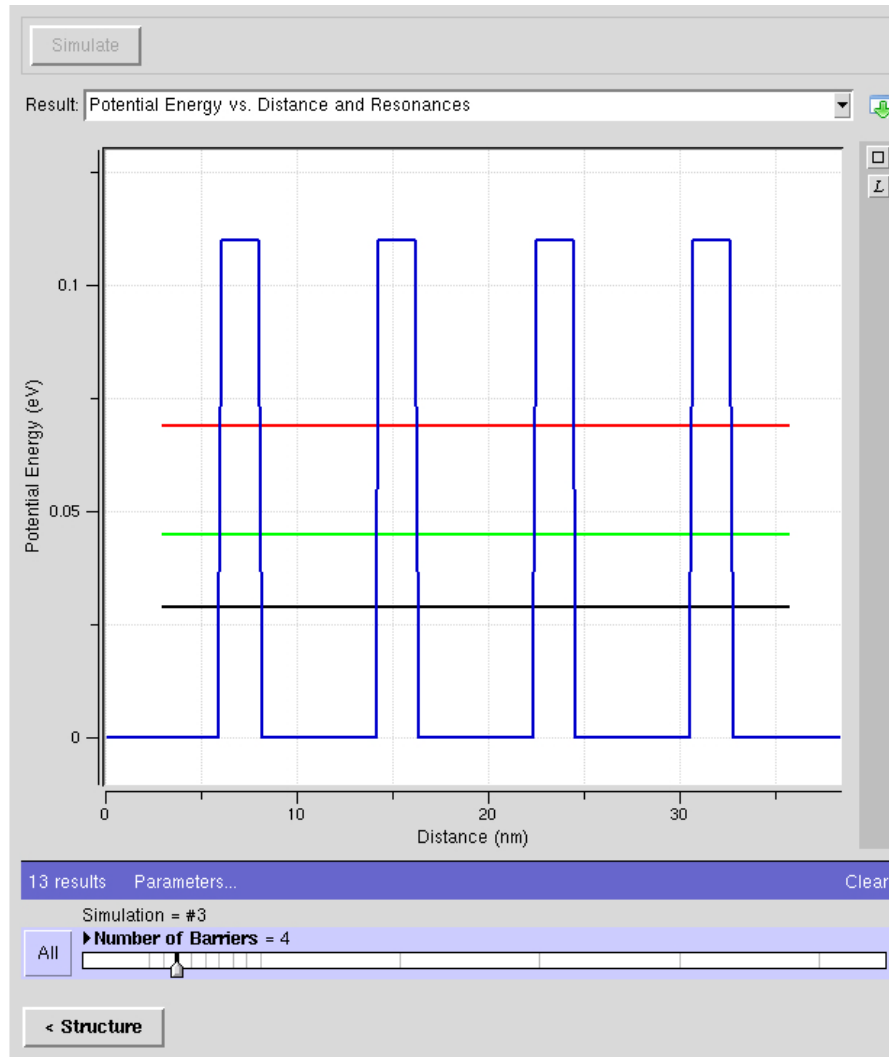


- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$



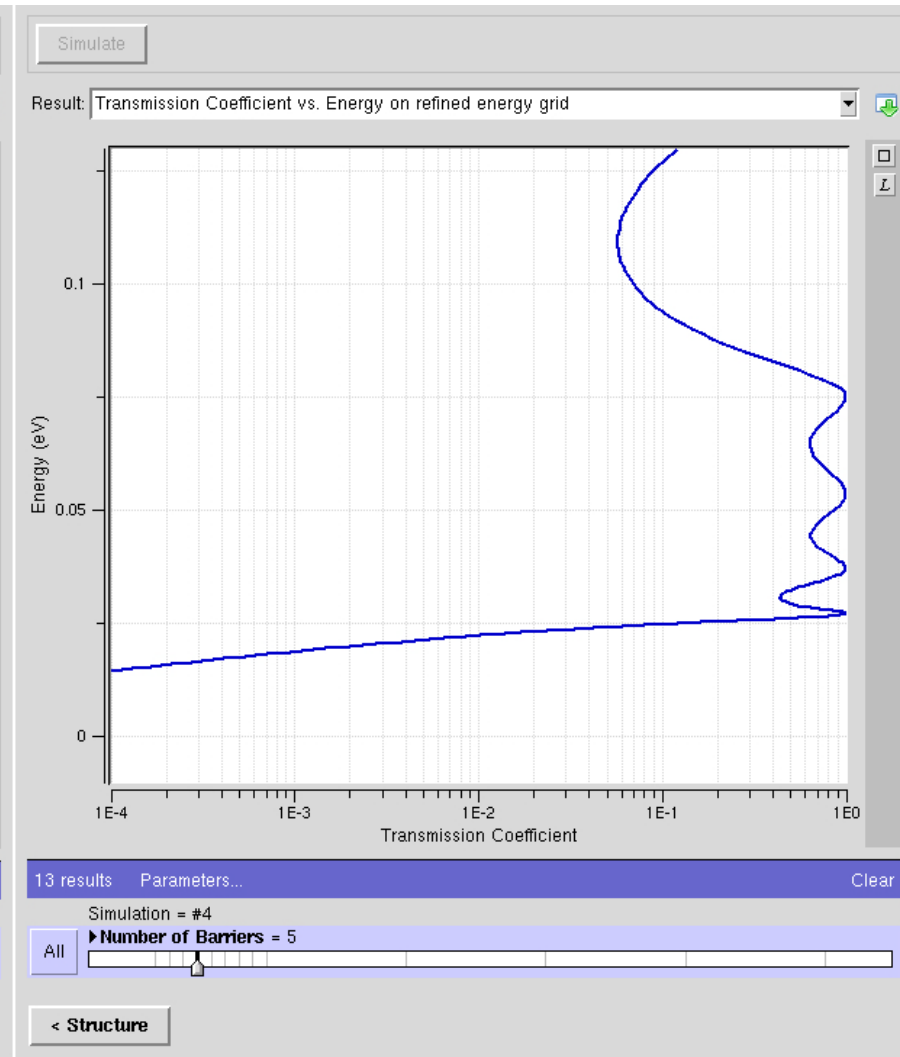
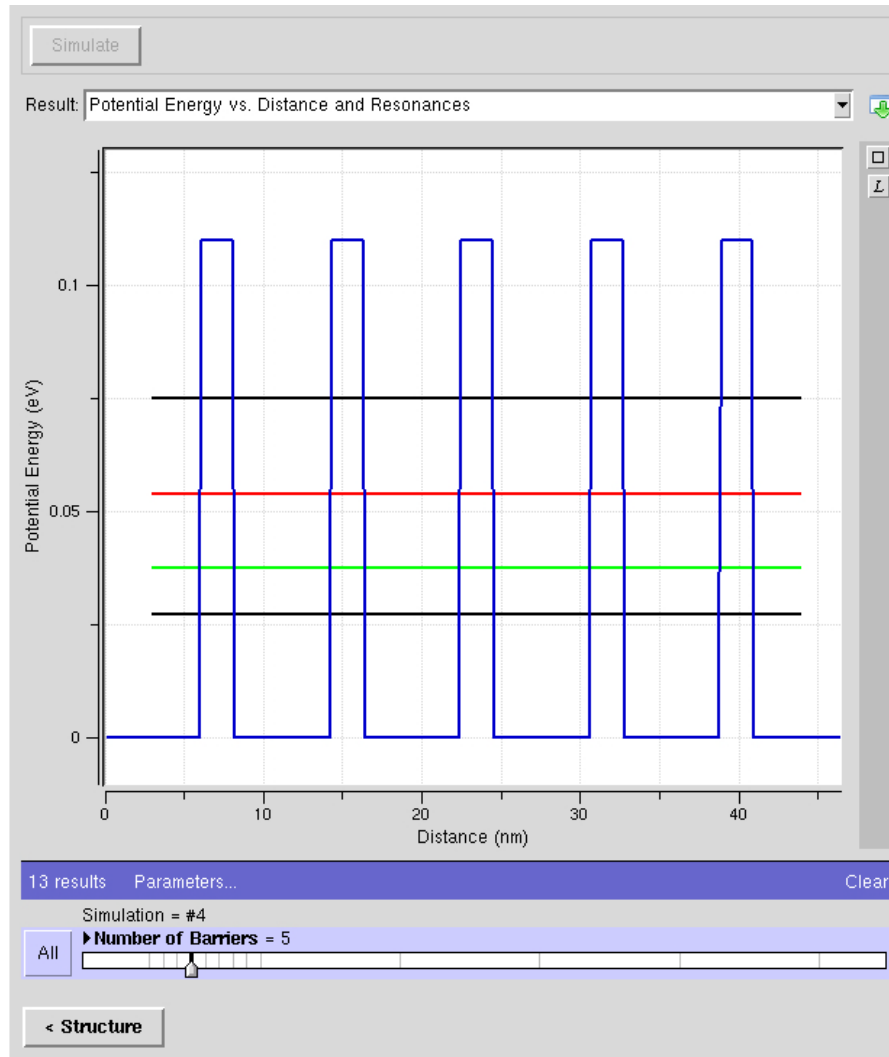
Bonding/Anti-bonding State

3 Wells => 3 Transmission Peaks



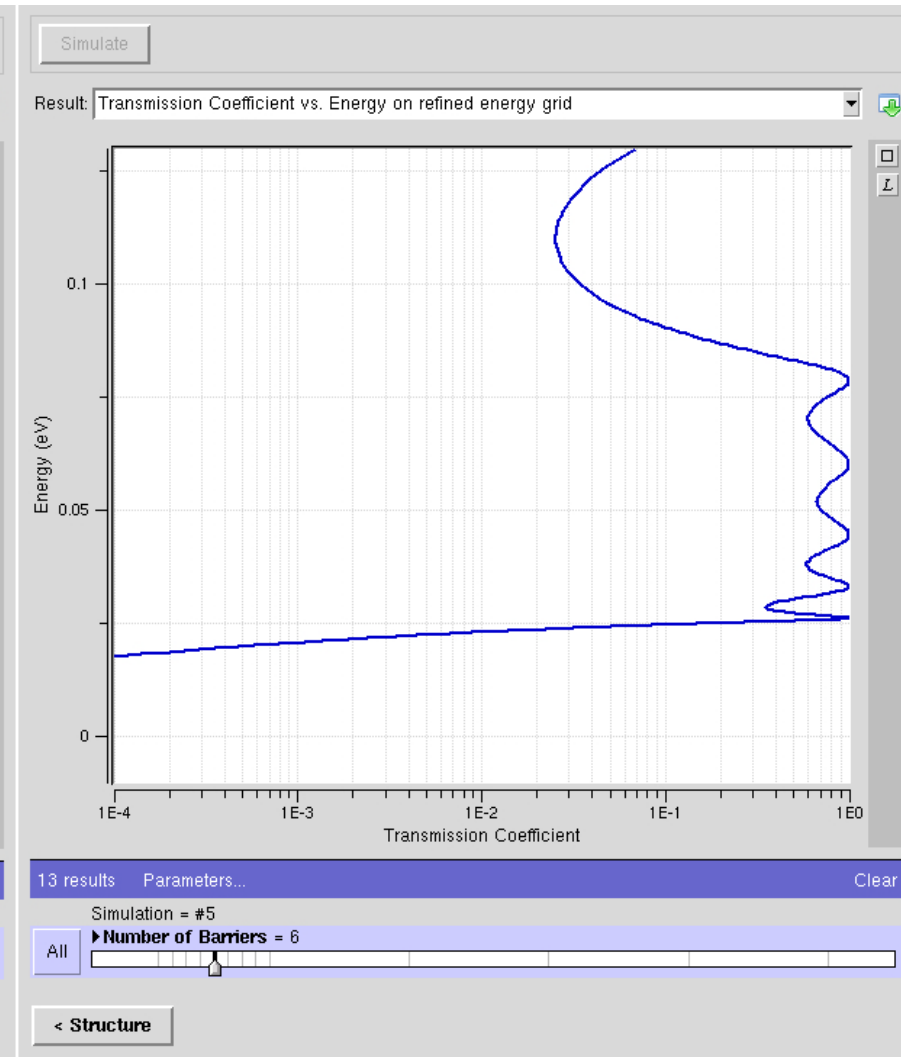
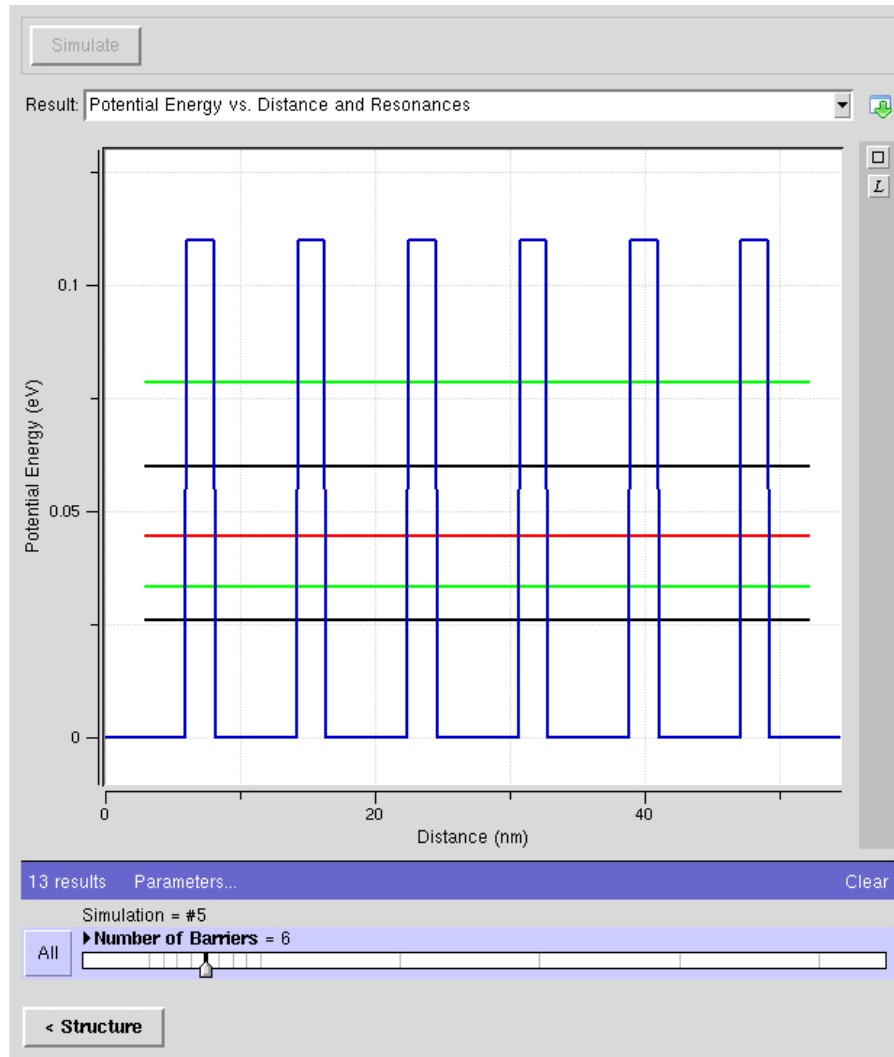
- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

4 Wells => 4 Transmission Peaks



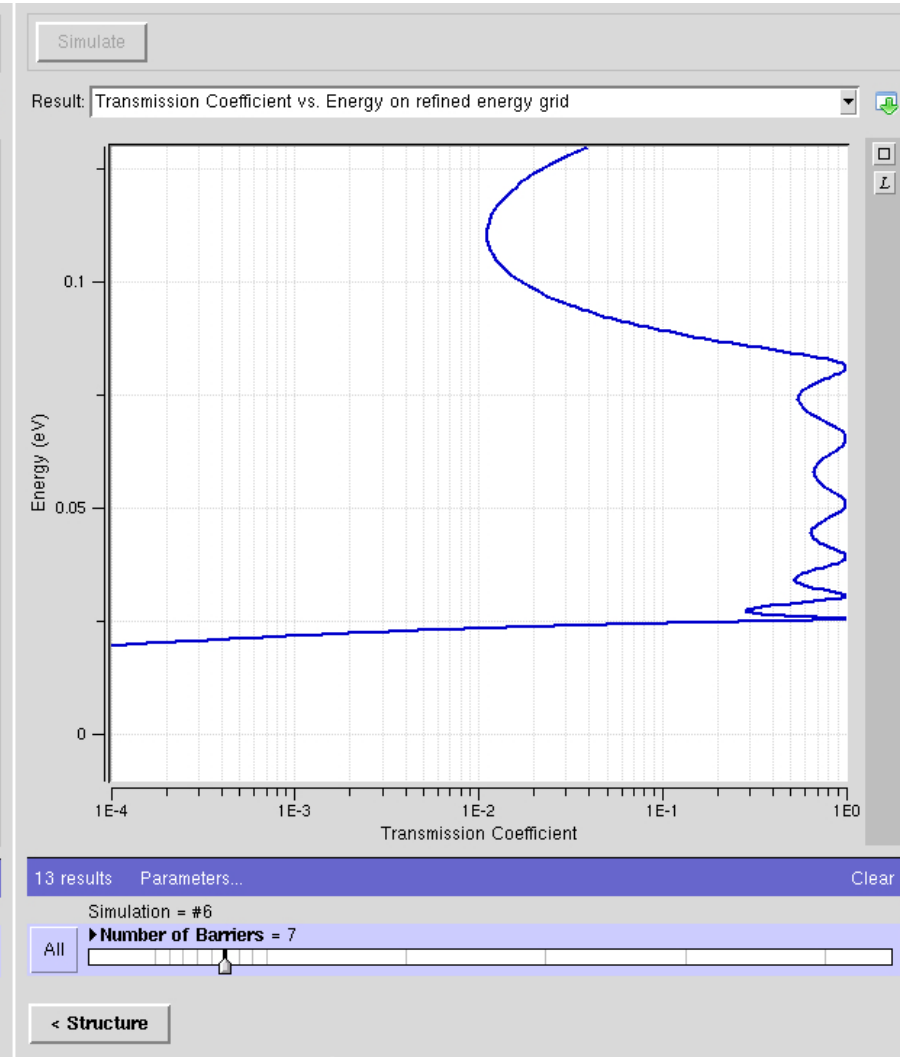
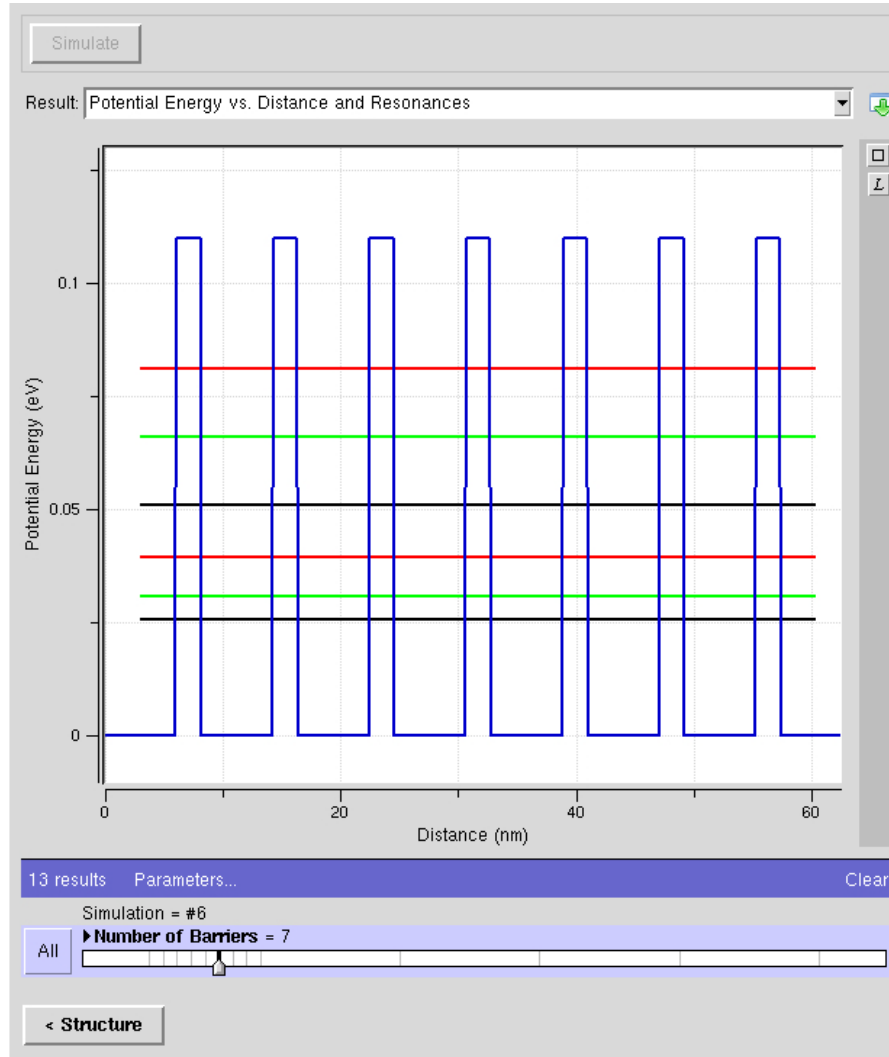
- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

5 Wells => 5 Transmission Peaks



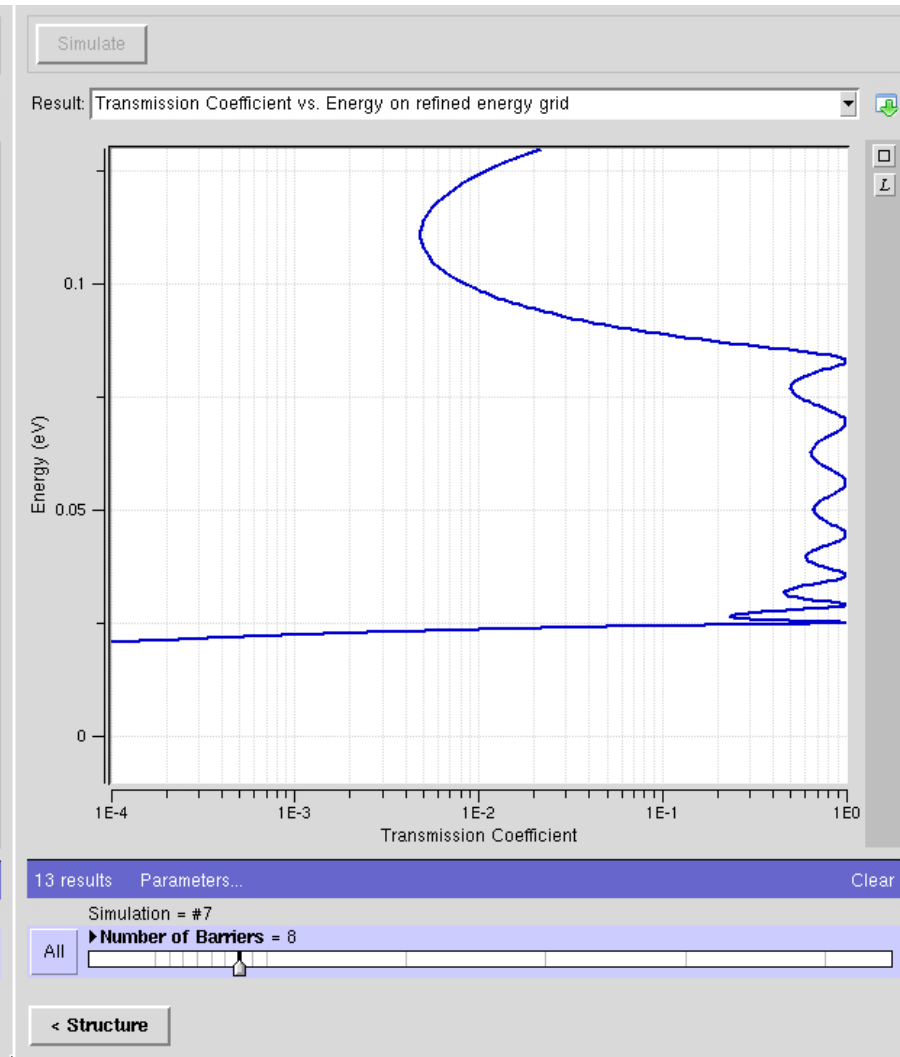
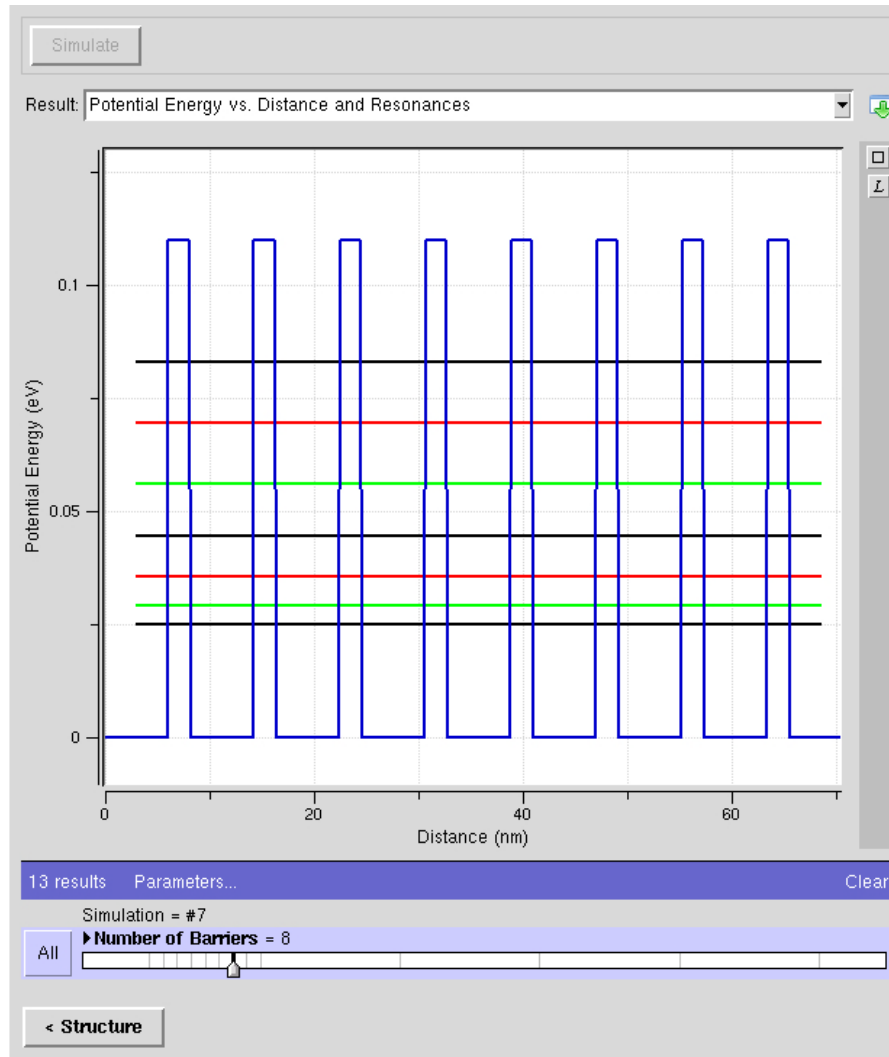
- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

6 Wells => 6 Transmission Peaks



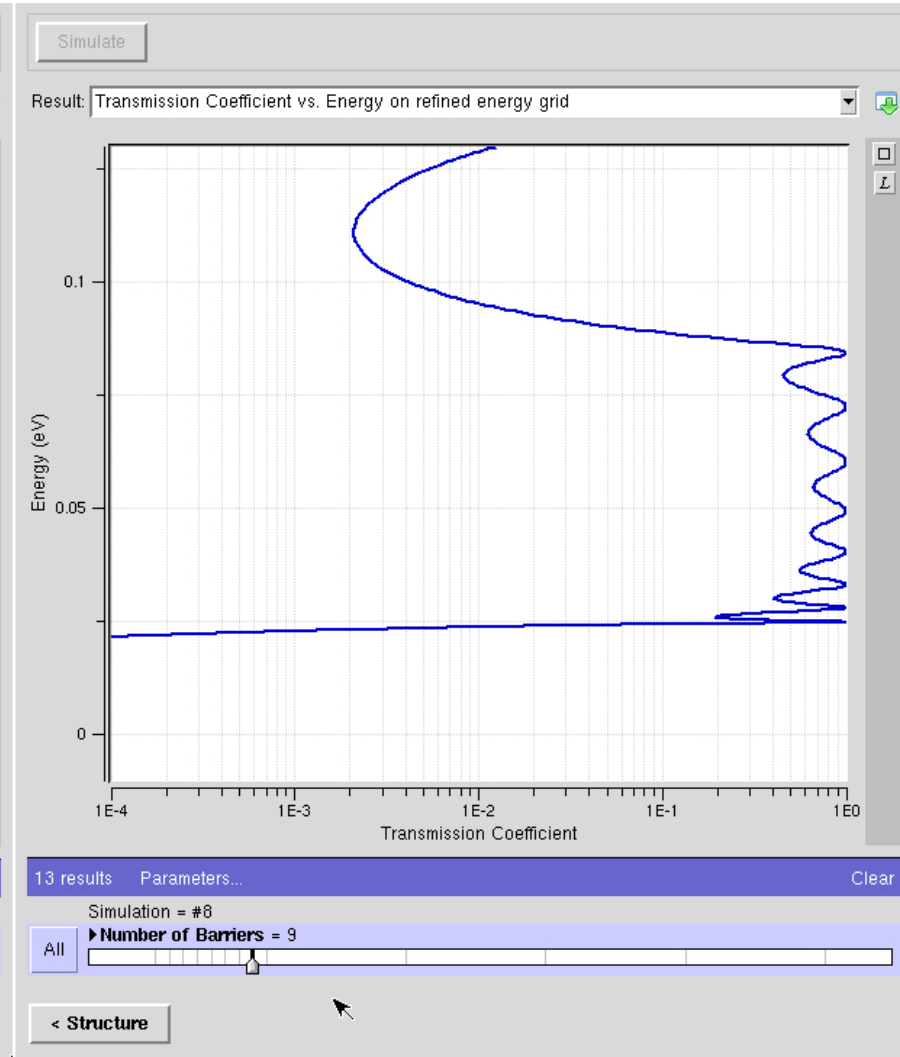
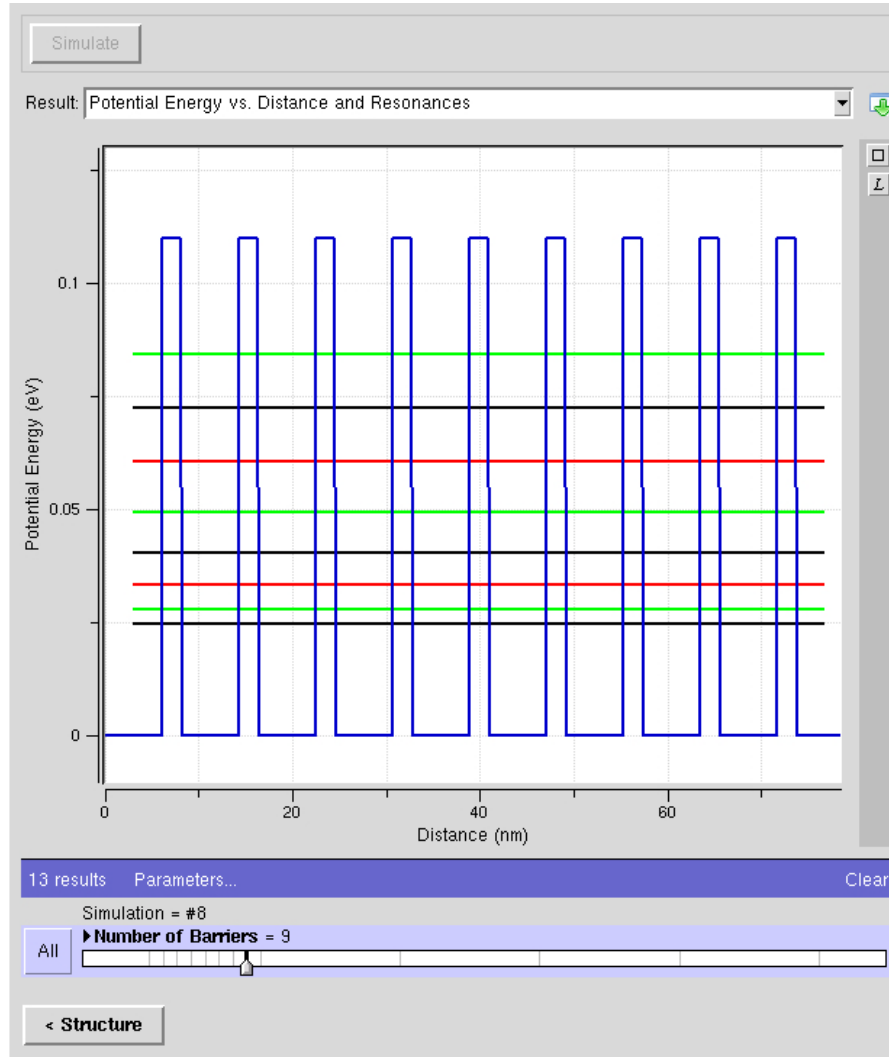
- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

7 Wells => 7 Transmission Peaks



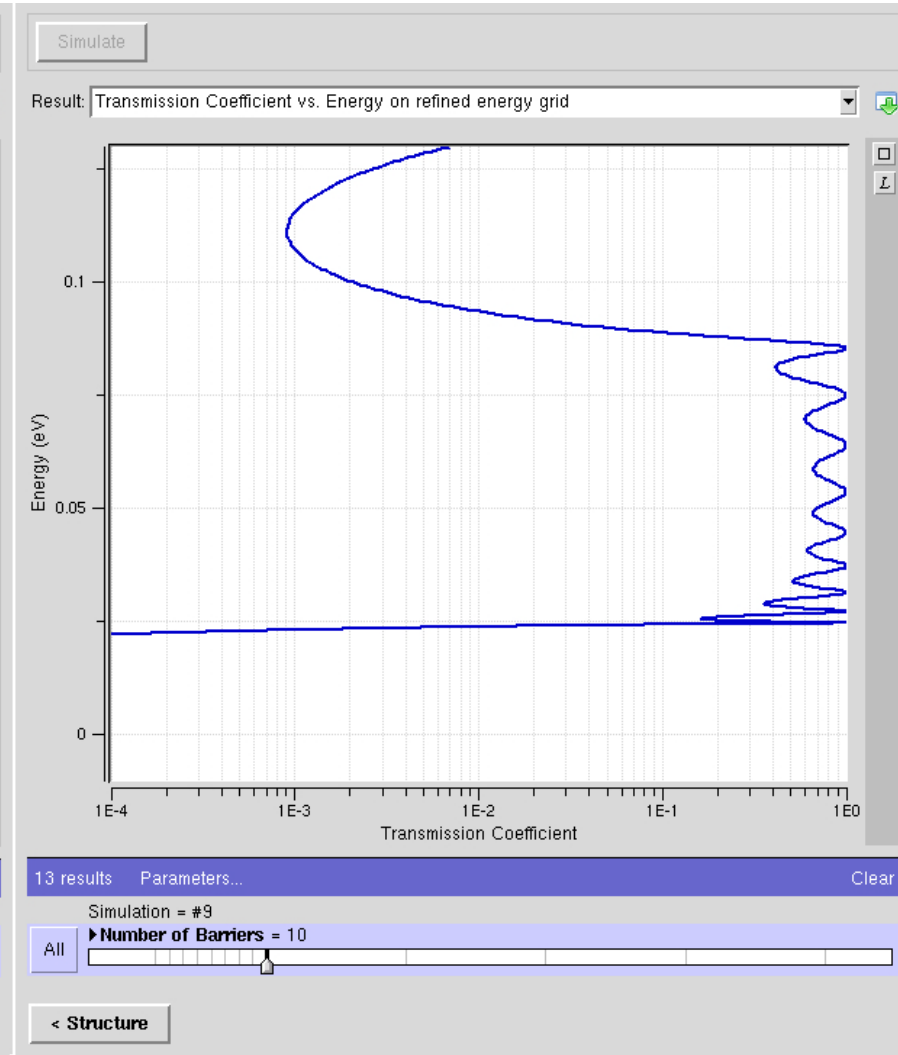
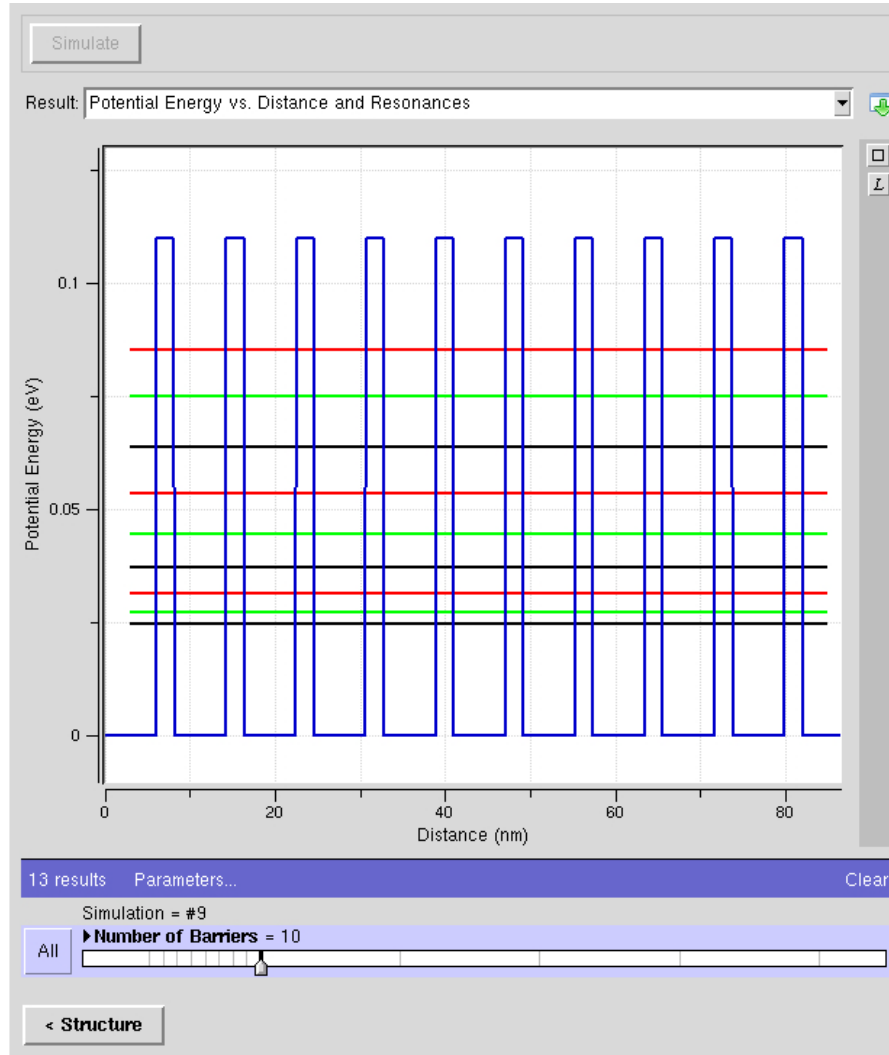
- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

8 Wells => 8 Transmission Peaks



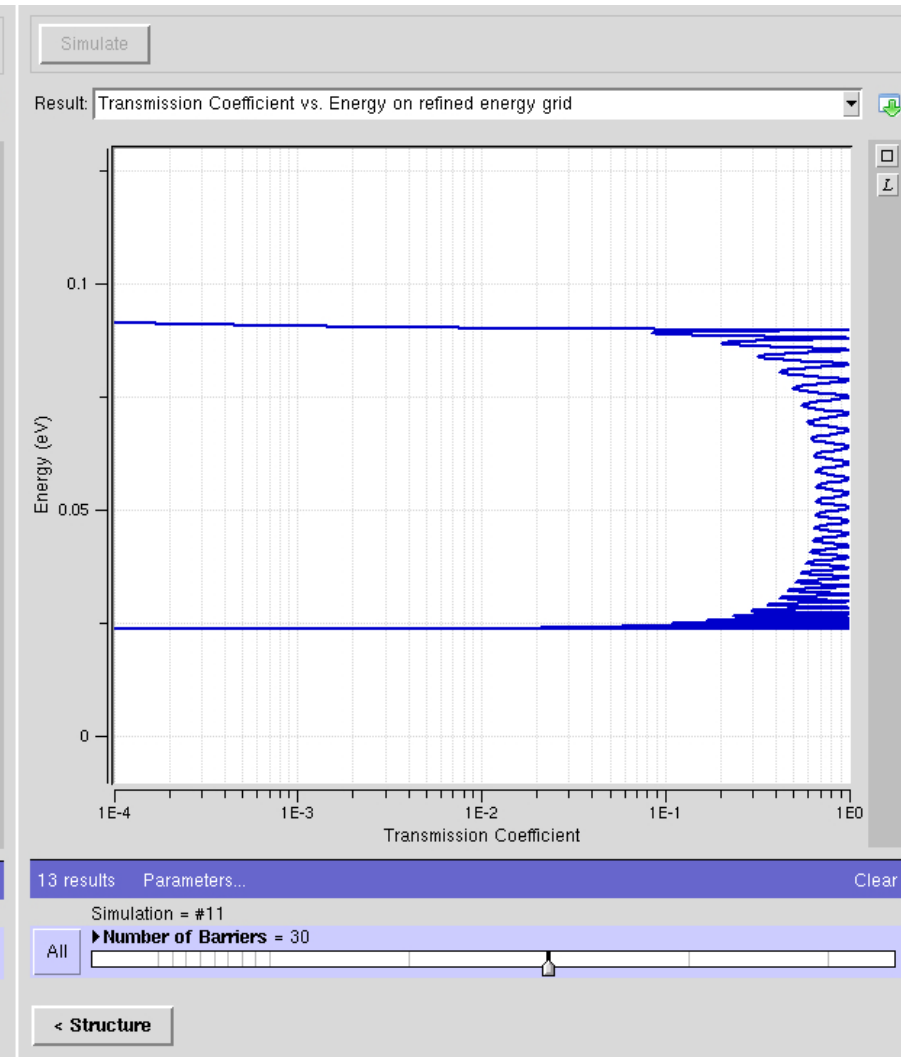
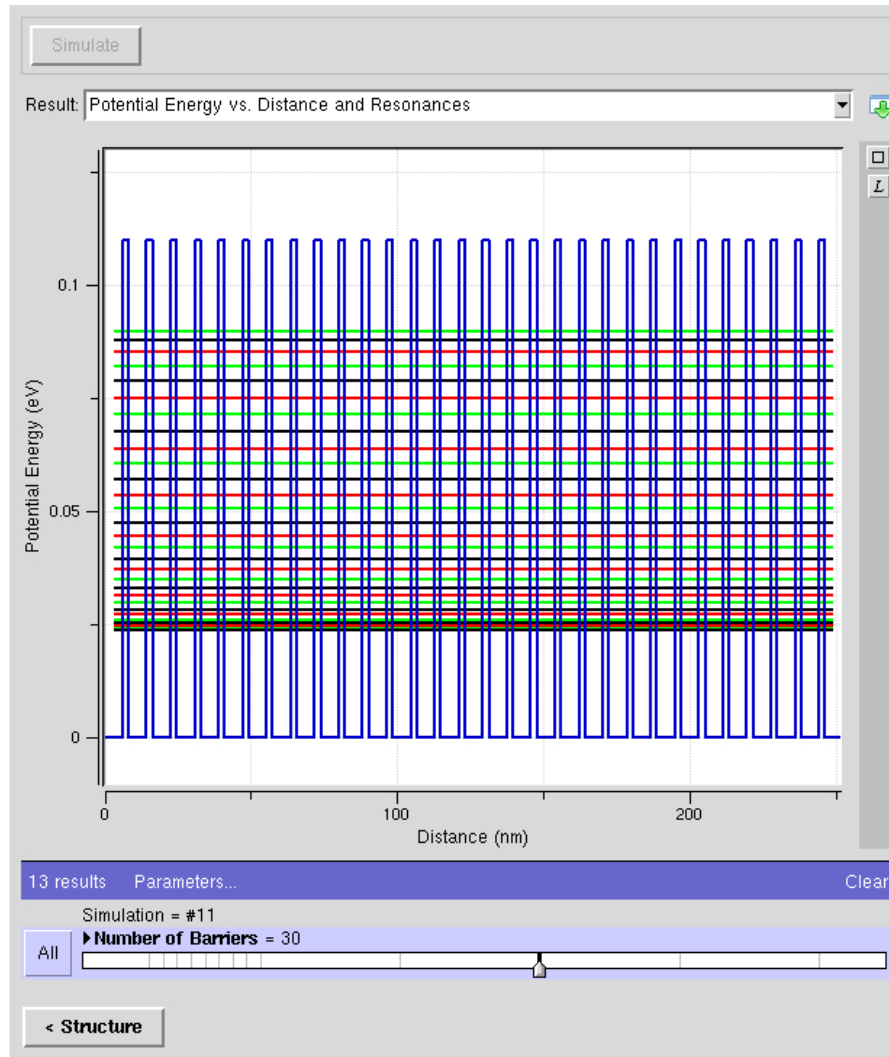
- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

9 Wells => 9 Transmission Peaks



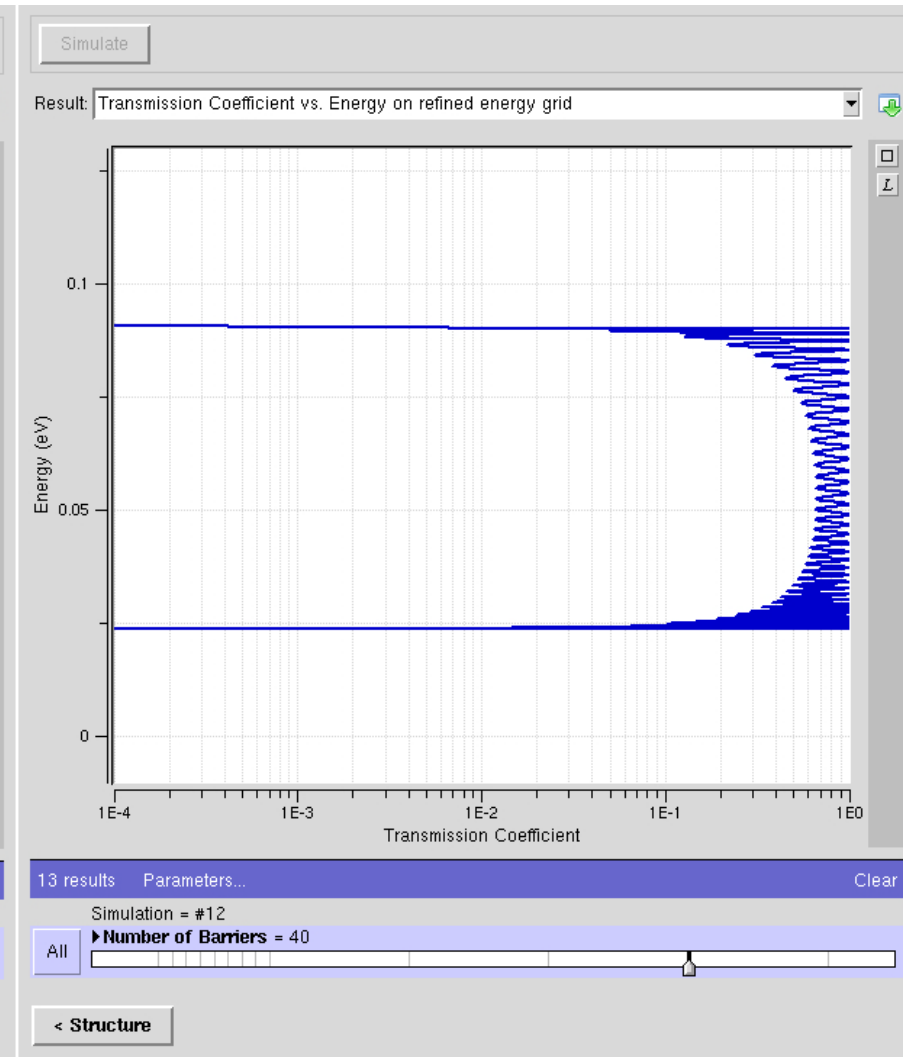
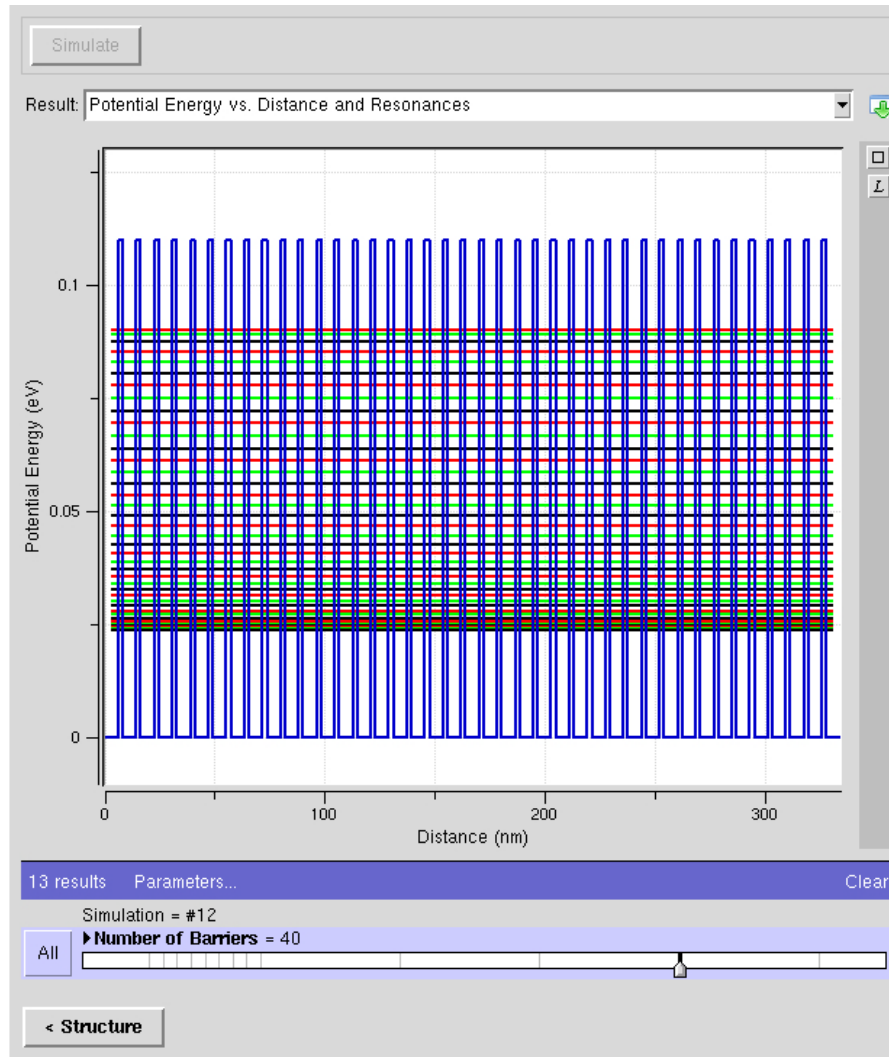
- Bandpass filter formed
- Band transmission not symmetric

29 Wells => 29 Transmission Peaks



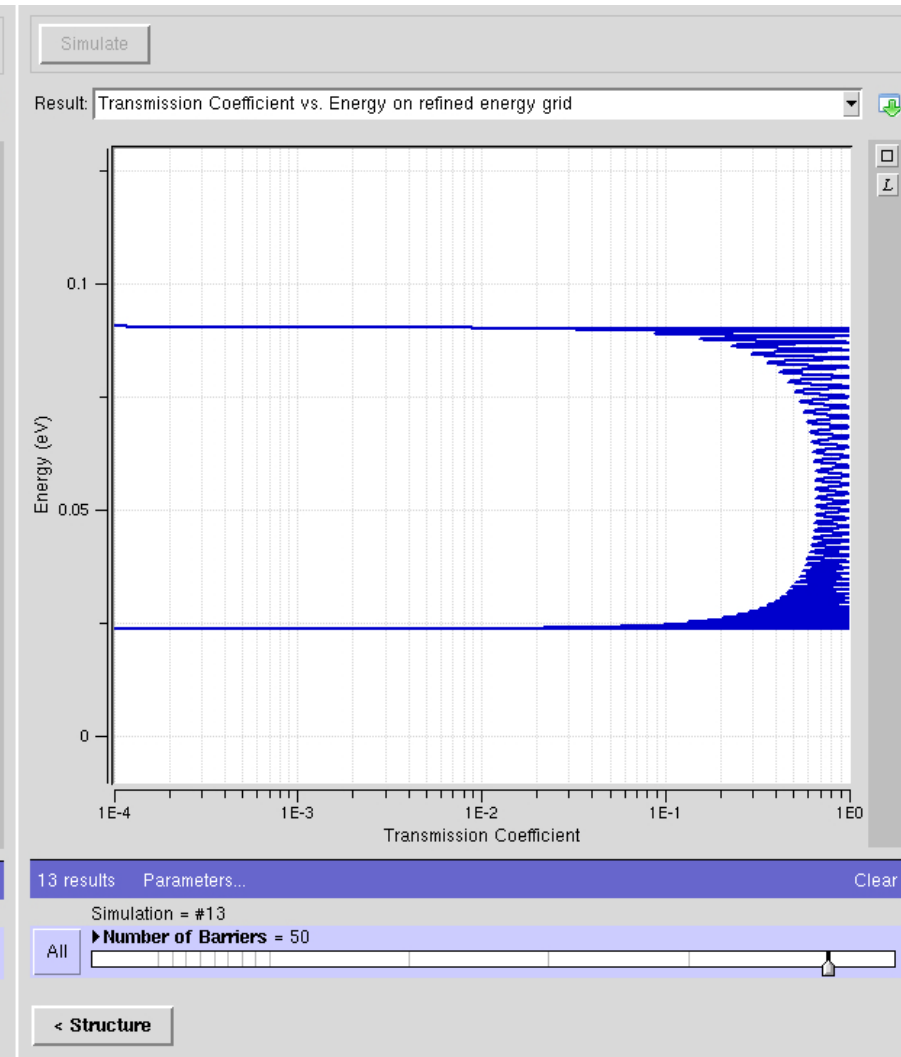
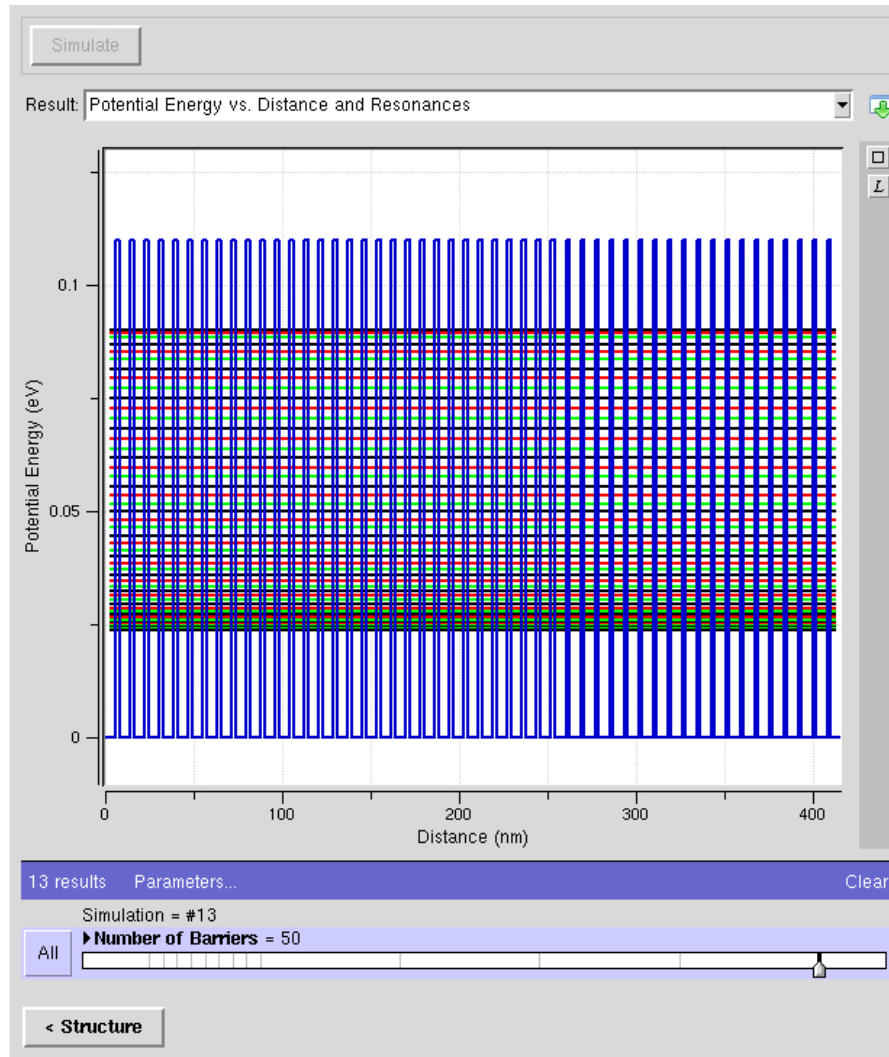
- Bandpass filter formed
- Band transmission not symmetric

39 Wells => 39 Transmission Peaks



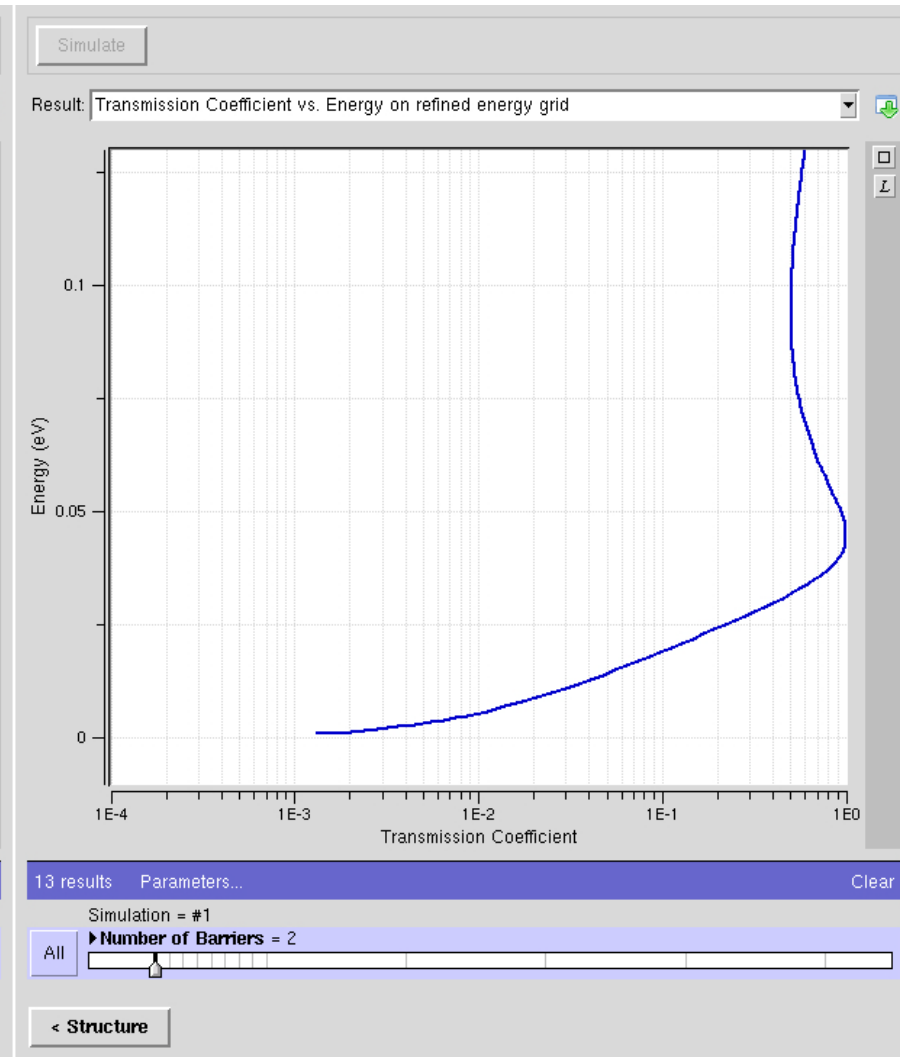
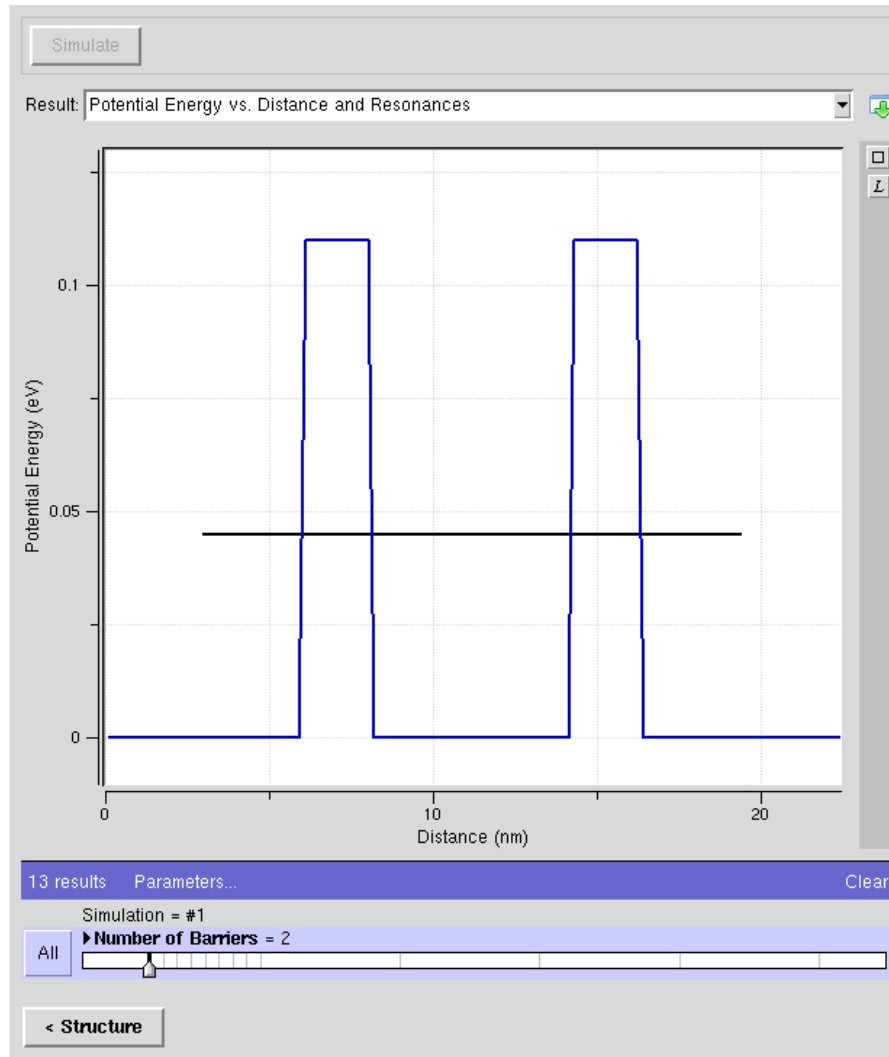
- Bandpass filter formed
- Band transmission not symmetric

49 Wells => 49 Transmission Peaks



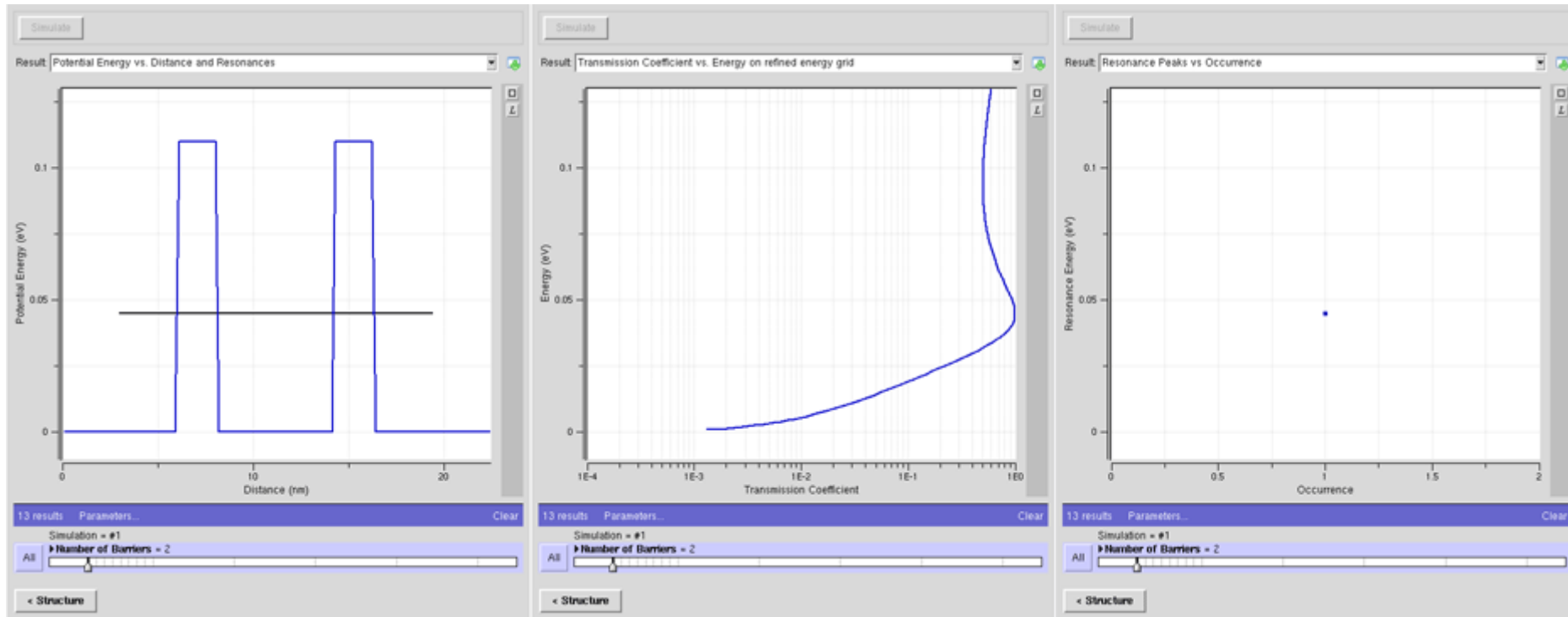
- Bandpass filter formed
- Band transmission not symmetric

N Wells => N Transmission Peaks



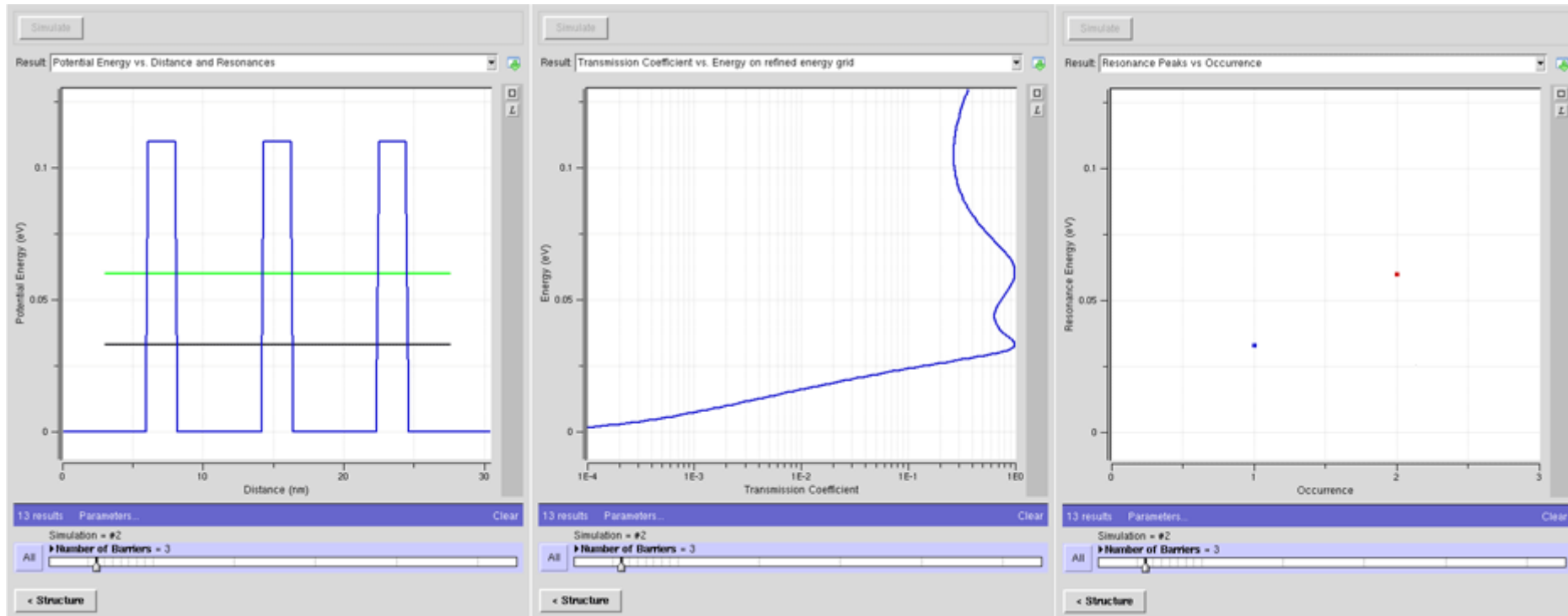
- Bandpass filter formed
- Band transmission not symmetric
- Bandpass sharpens with increasing number of wells

1 Well => 1 Transmission Peak => 1 State



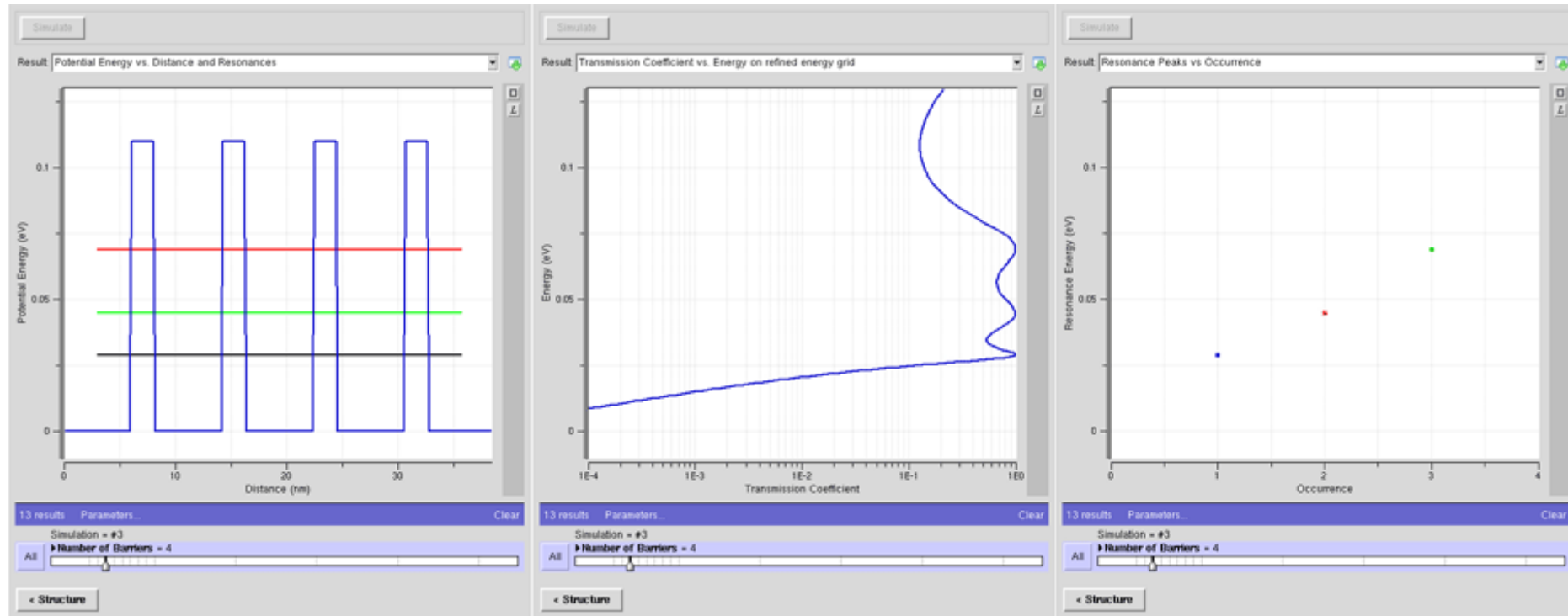
- Bandpass filter formed
- Band transmission not symmetric
- Bandpass sharpens with increasing number of wells

2 Wells => 2 Transmission Peaks => 2 States



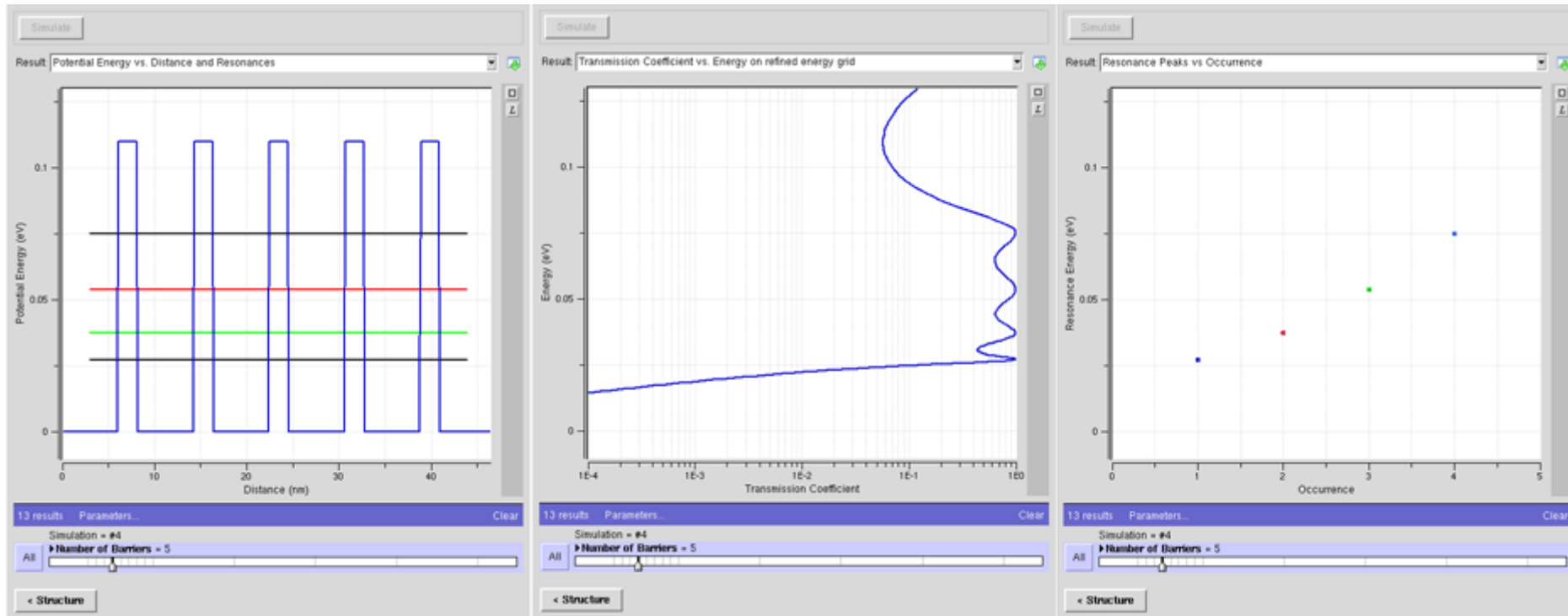
- Bandpass filter formed
- Band transmission not symmetric

3 Wells => 3 Transmission Peaks => 3 States



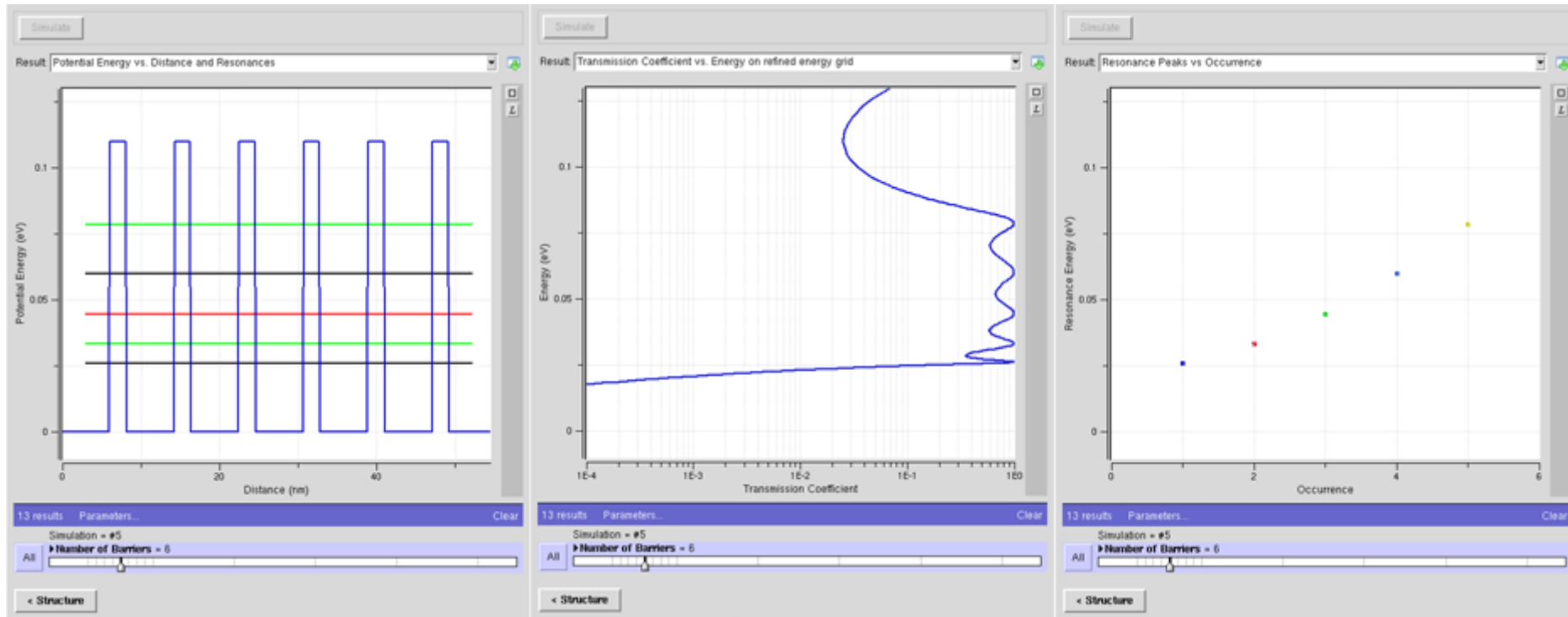
- Bandpass filter formed
- Band transmission not symmetric

4 Wells => 4 Transmission Peaks => 4 States



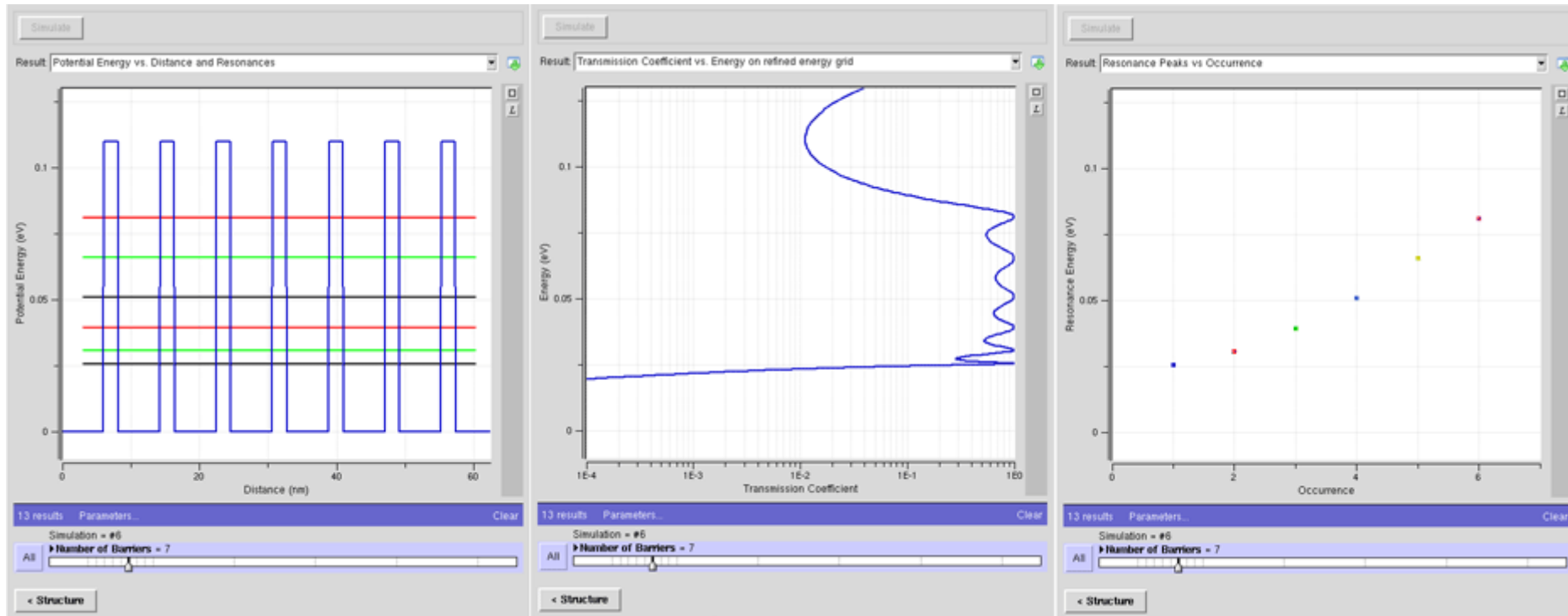
- Bandpass filter formed
- Band transmission not symmetric

5 Wells => 5 Transmission Peaks => 5 States



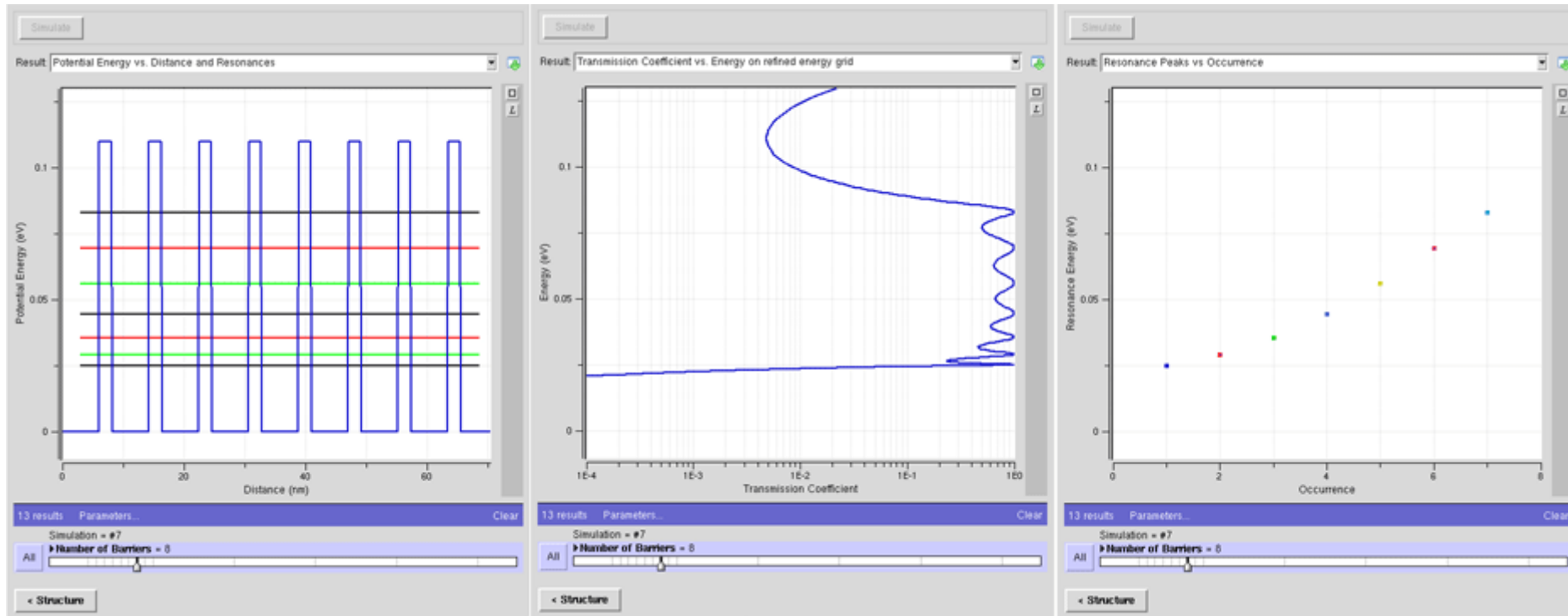
- Bandpass filter formed
- Band transmission not symmetric

6 Wells => 6 Transmission Peaks => 6 States



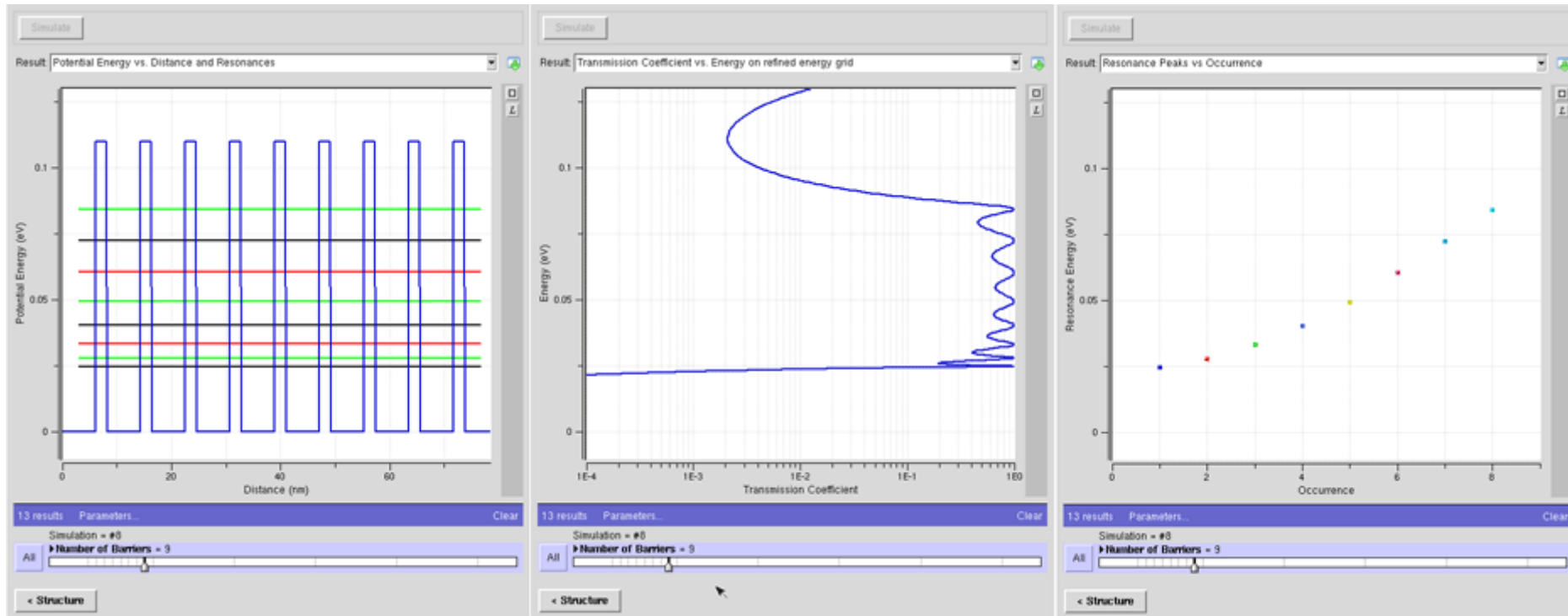
- Bandpass filter formed
- Band transmission not symmetric

7 Wells => 7 Transmission Peaks => 7 States



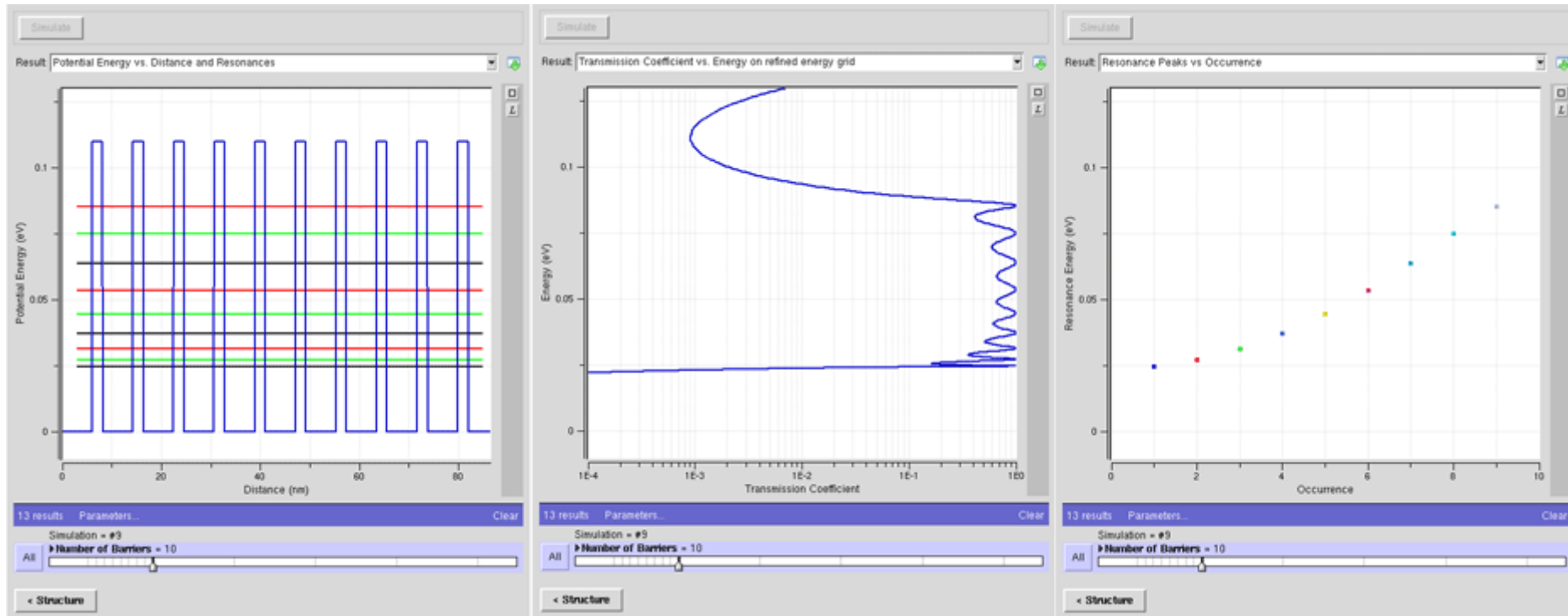
- Bandpass filter formed
- Band transmission not symmetric

8 Wells => 8 Transmission Peaks => 8 States



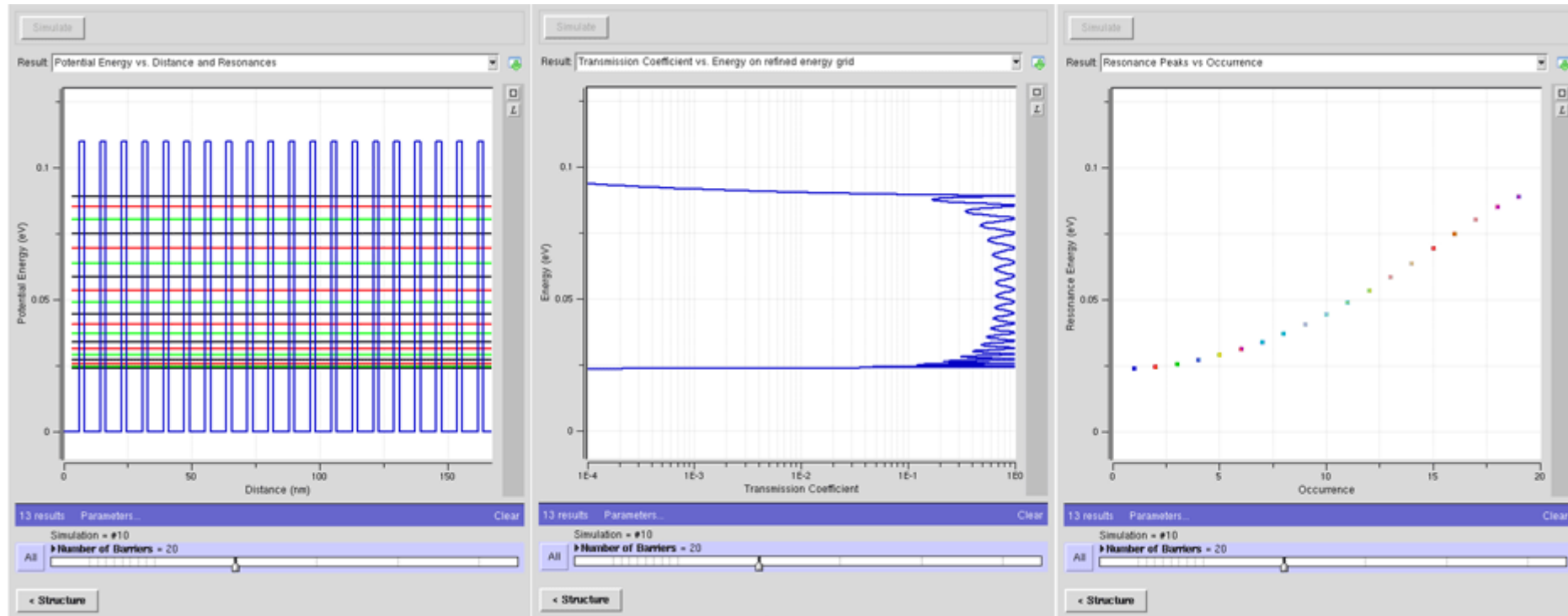
- Bandpass filter formed
- Band transmission not symmetric

9 Wells => 9 Transmission Peaks => 9 States



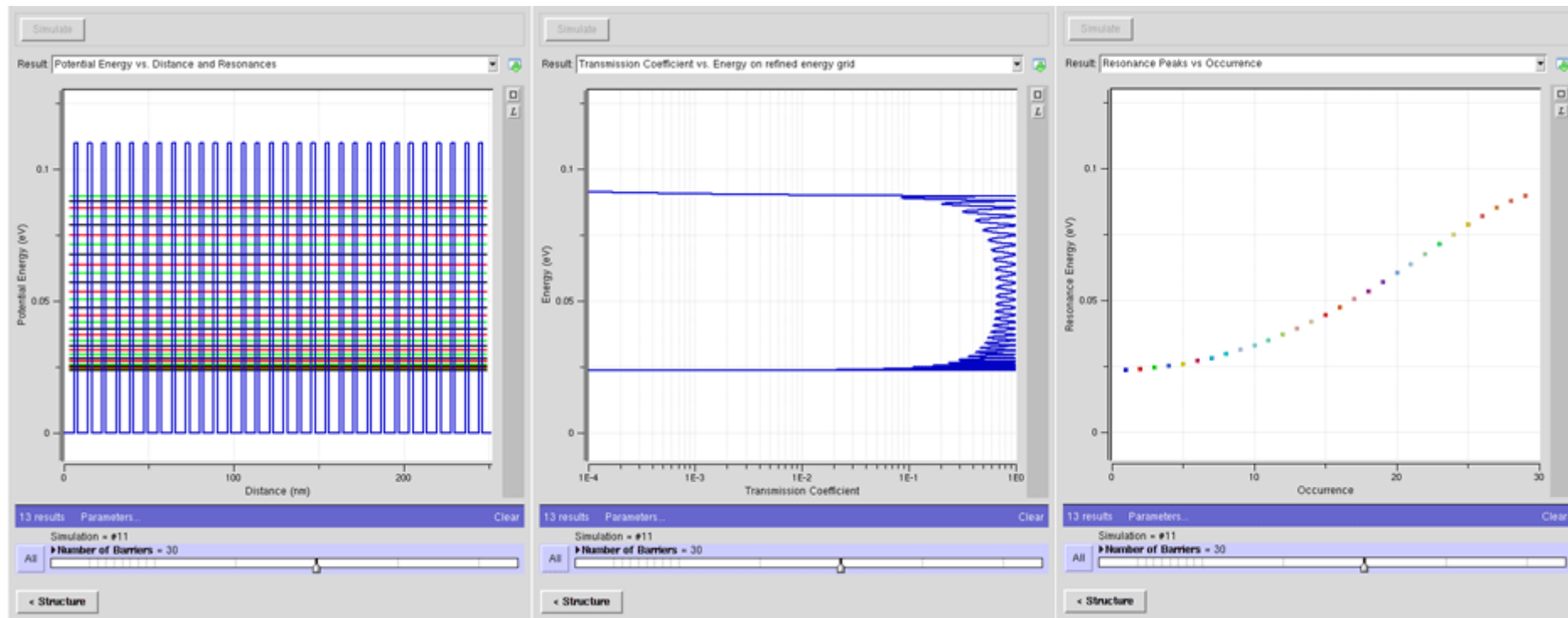
- Bandpass filter formed
- Band transmission not symmetric

19 Wells => 19 Transmission Peaks => 19 States



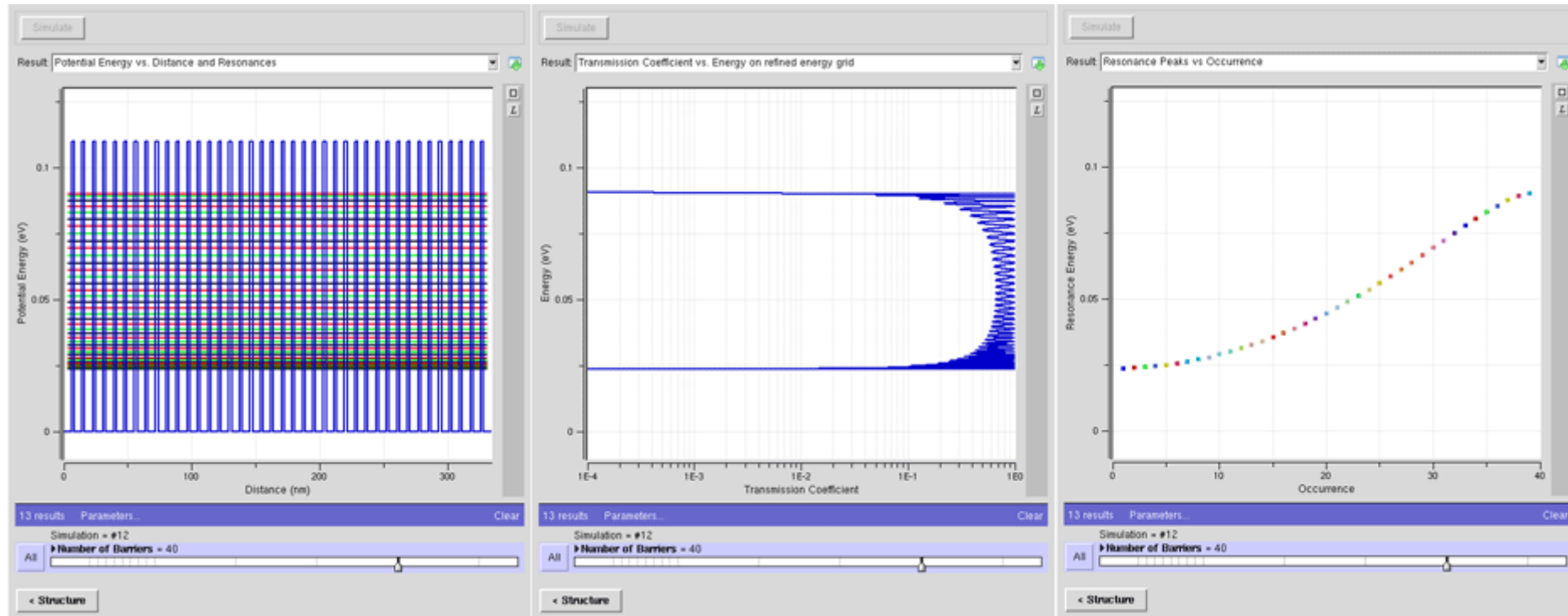
- Bandpass filter formed
- Band transmission not symmetric

29 Wells => 29 Transmission Peaks => 29 States



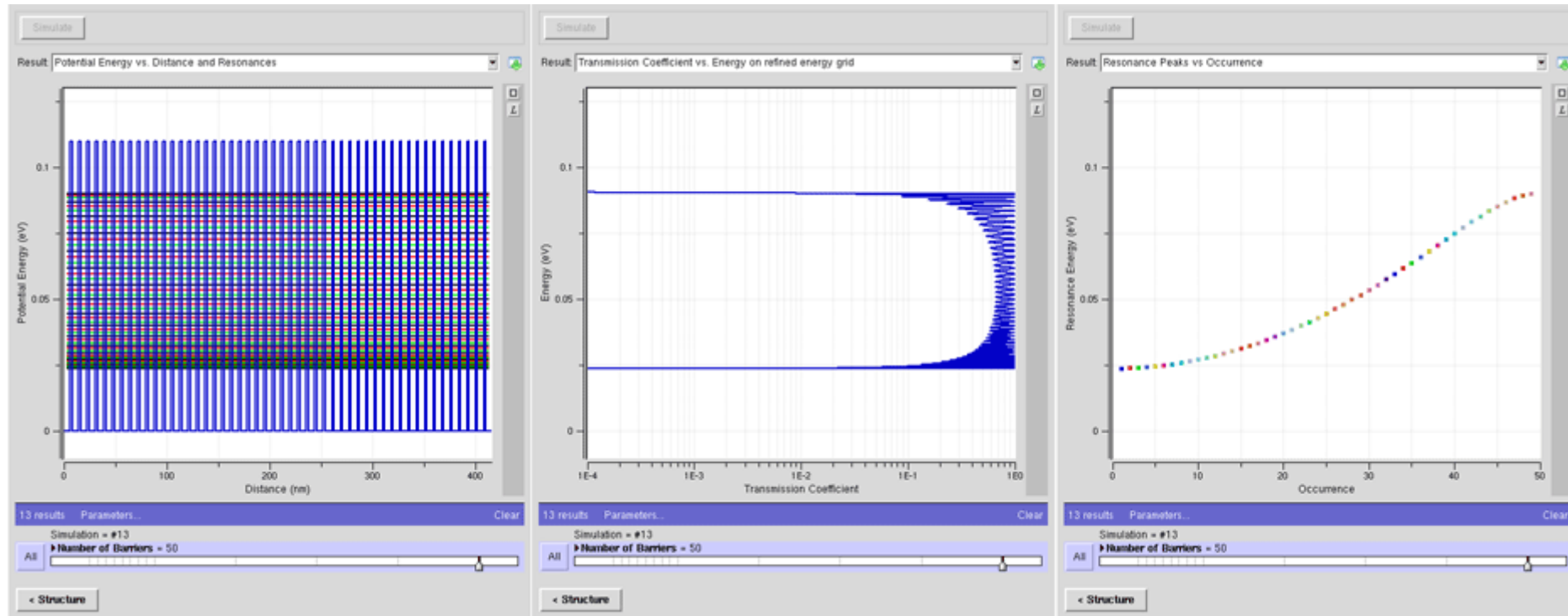
- Bandpass filter formed
- Band transmission not symmetric

39 Wells => 39 Transmission Peaks => 39 States



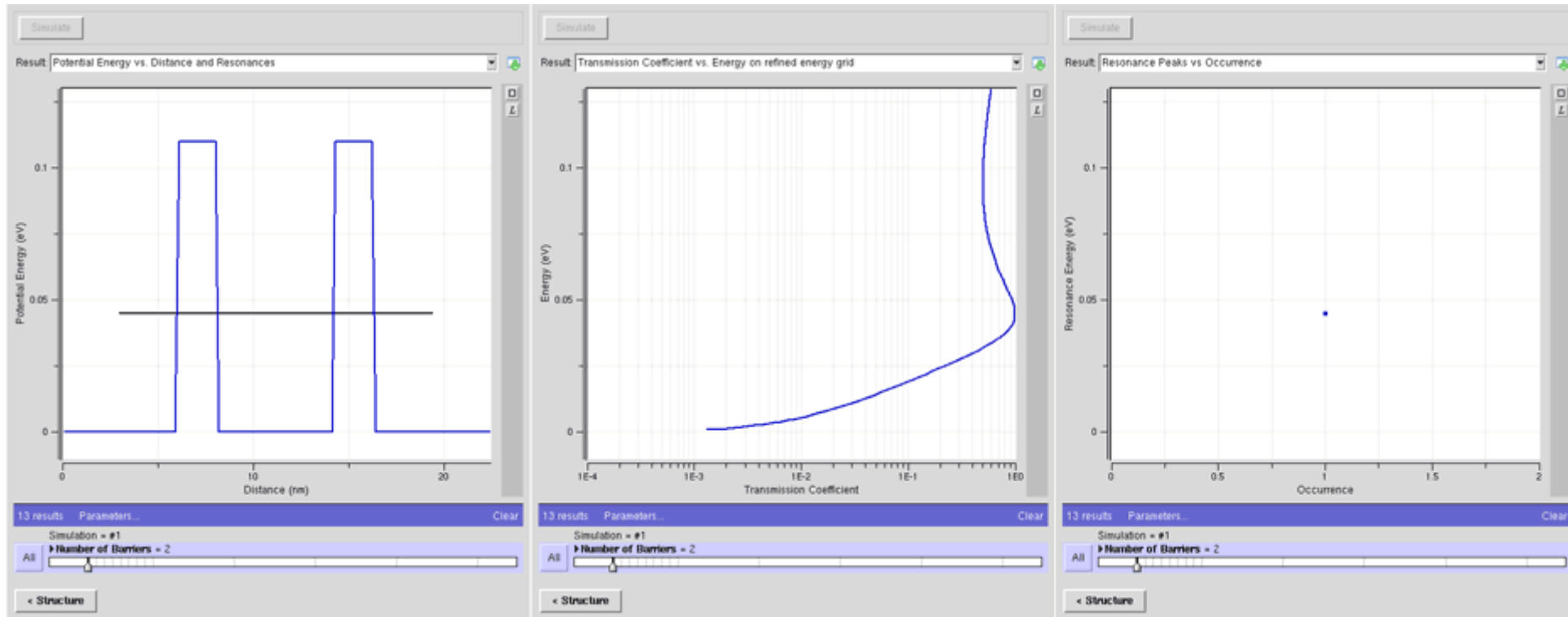
- Bandpass filter formed
- Band transmission not symmetric

49 Wells => 49 Transmission Peaks => 49 States



- Bandpass filter formed
- Band transmission not symmetric
- Cosine-like band formed
- Band is not symmetric

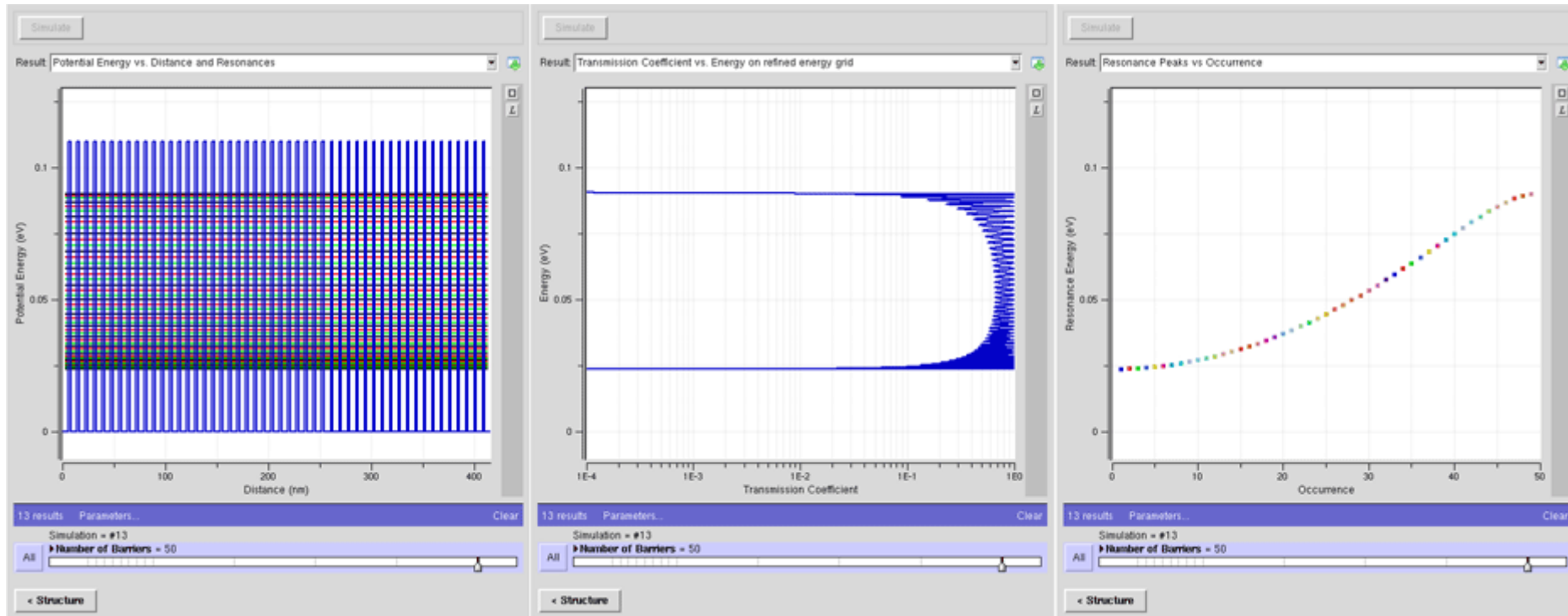
N Wells => N Transmission Peaks => N States



- Bandpass filter formed
- Band transmission not symmetric
- Cosine-like band formed
- Band is not symmetric

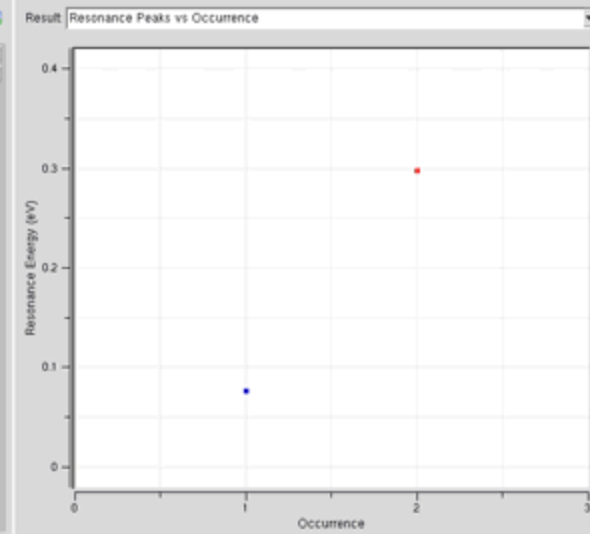
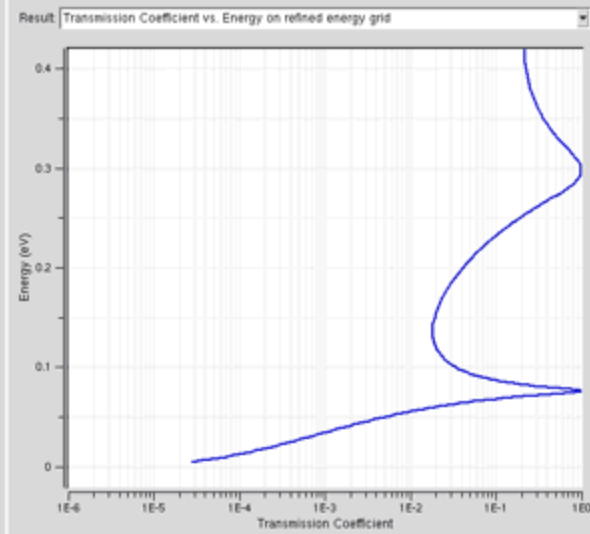
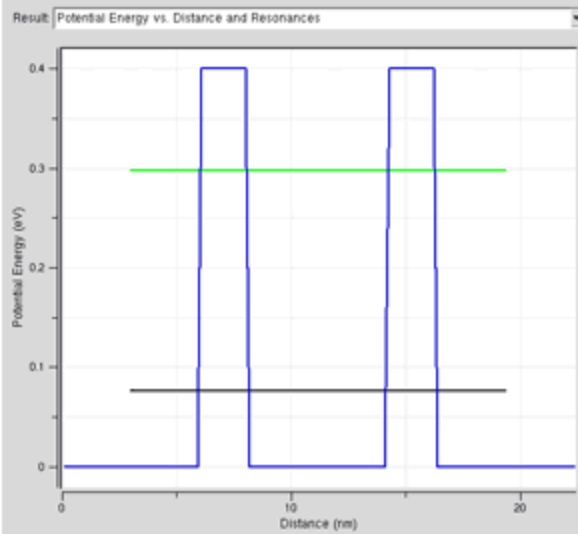
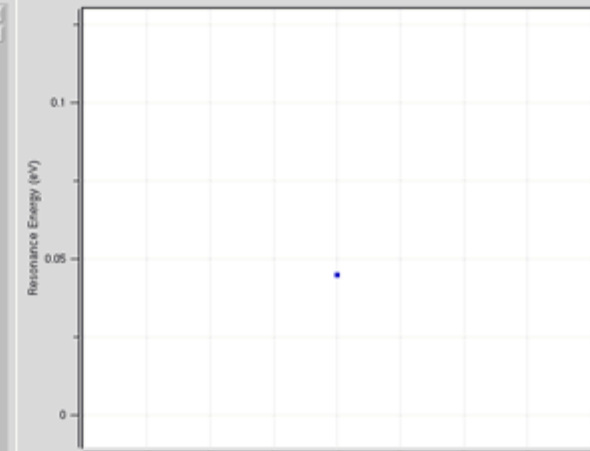
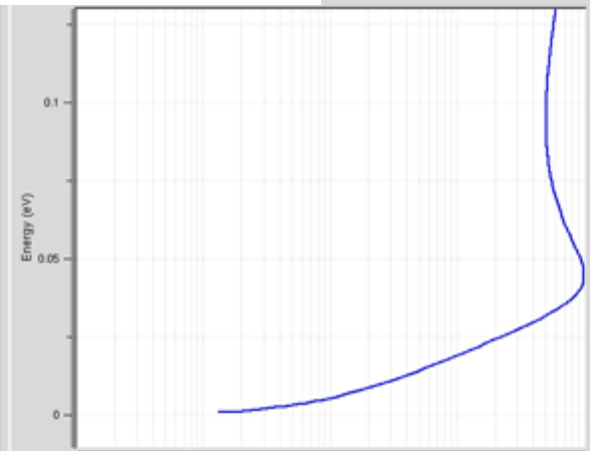
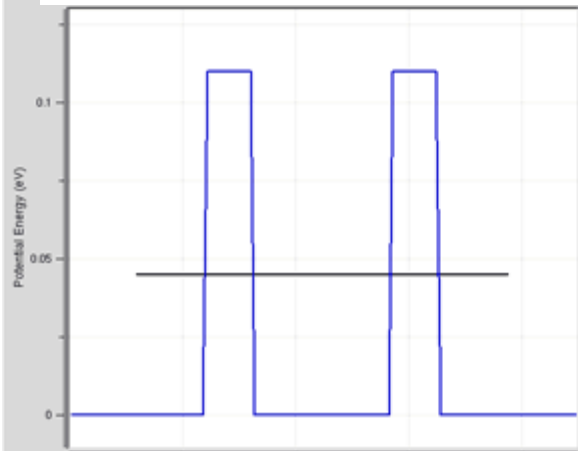
N Wells => N States => 1 Band

- $V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$ => ground state in each well
=> what if there were excited states in each well => $V_b=400\text{meV}$



N Wells => 2N States => 2 Bands

Vb=110meV, W=6nm, B=2nm



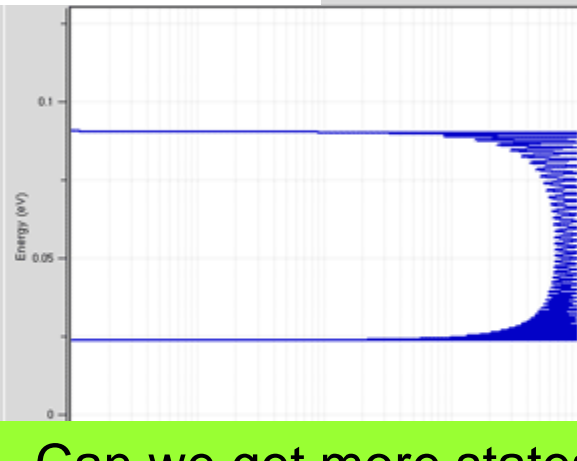
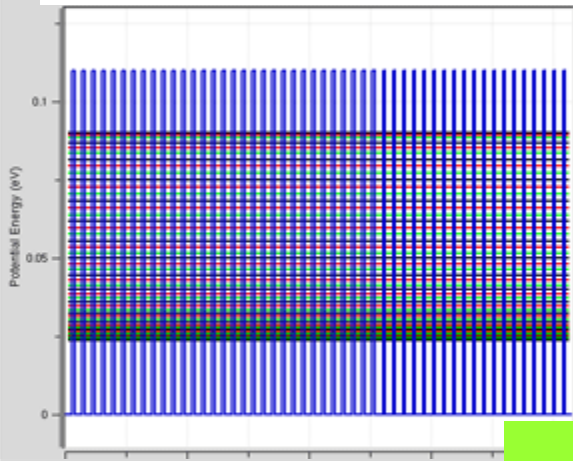
Vb=400meV, W=6nm, B=2nm

Simulation = #1
Number of Barriers = 2
< Structure

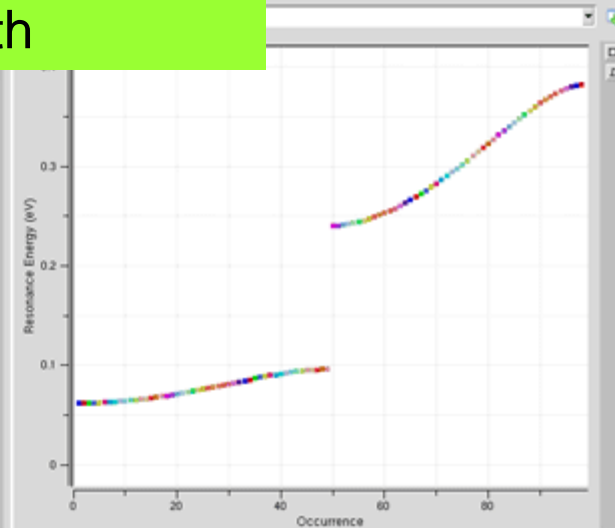
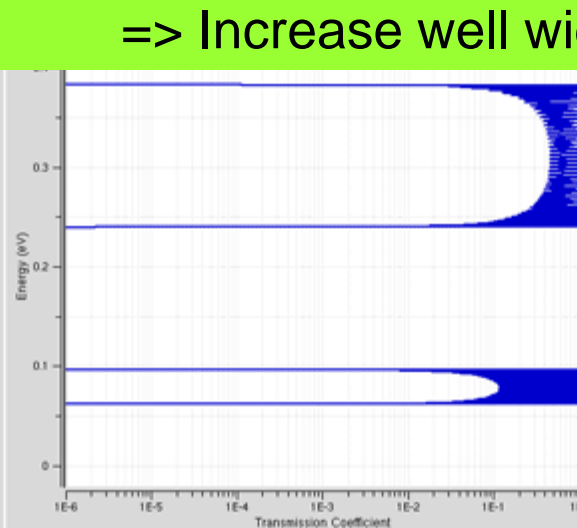
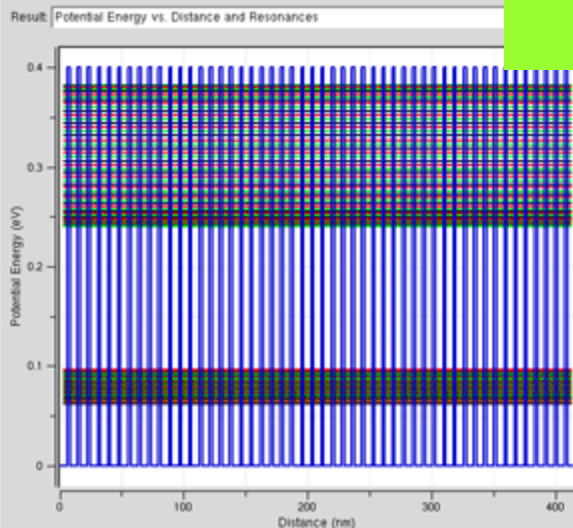
N Wells => 2N States => 2 Bands

$V_b=110\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

1 state/well => 1 band



Can we get more states/well?
=> Increase well width



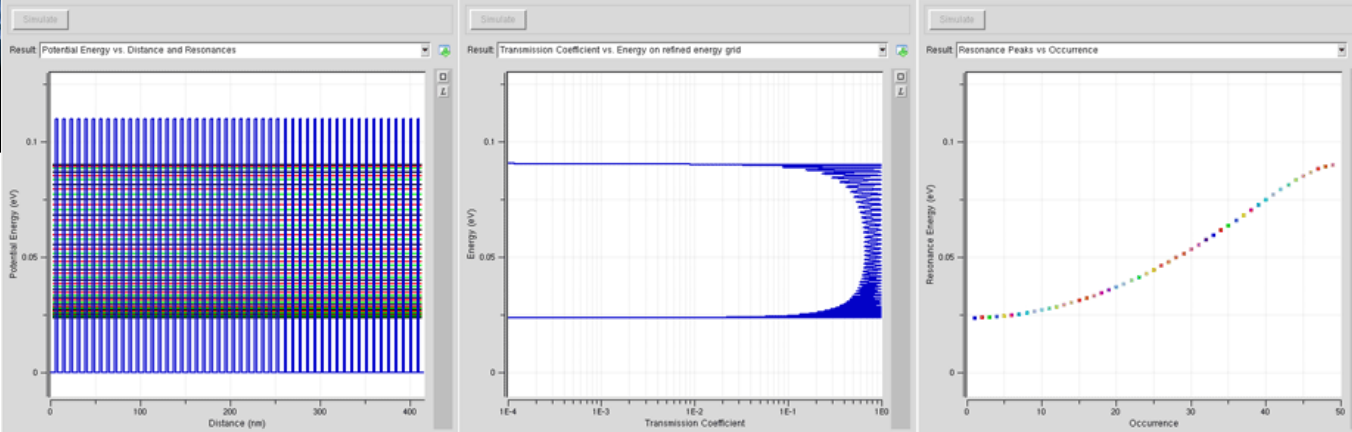
$V_b=400\text{meV}$, $W=6\text{nm}$, $B=2\text{nm}$

2 states/well => 2 bands

X States/Well => X Bands

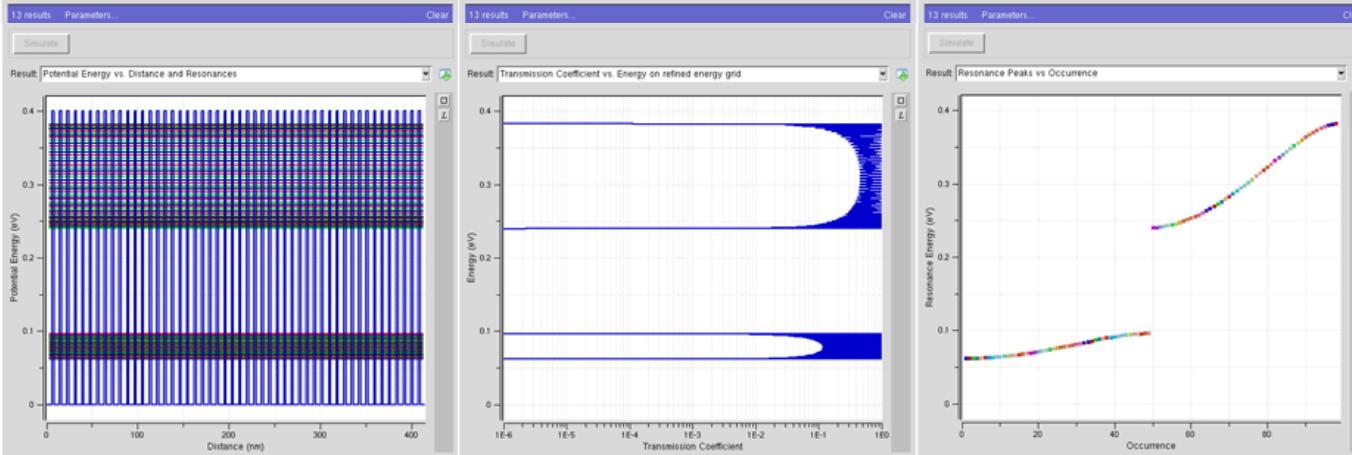
$V_b=110\text{meV}$,
 $W=6\text{nm}$, $B=2\text{nm}$

1 state/well
=> 1 band



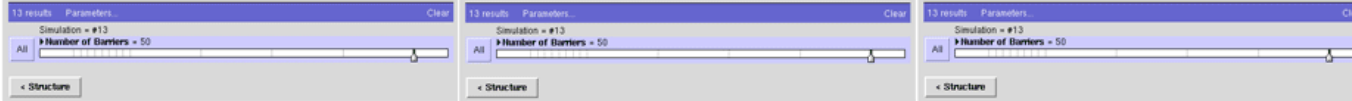
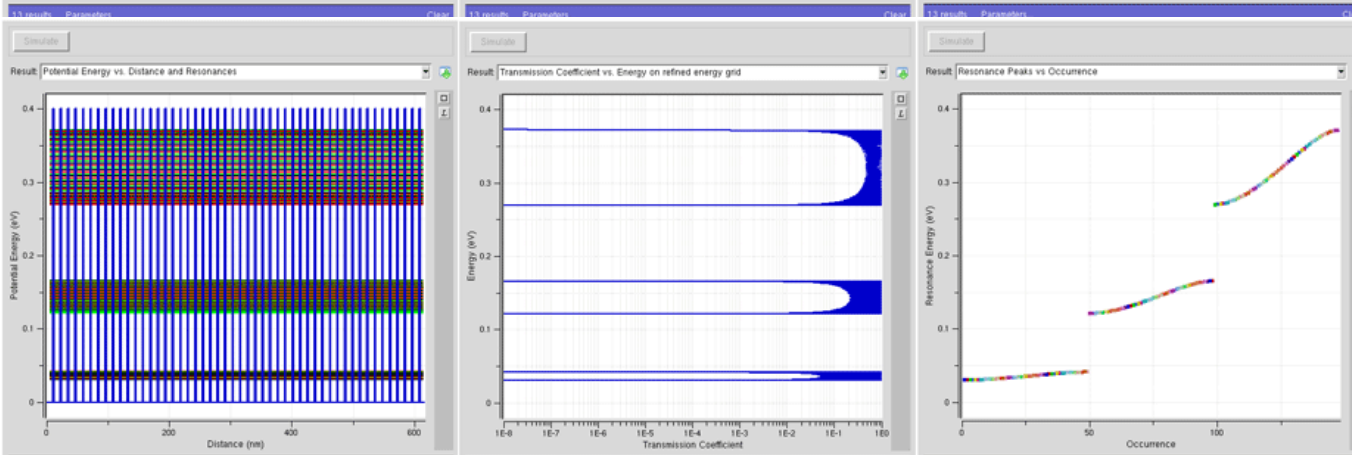
$V_b=400\text{meV}$
 $W=6\text{nm}$, $B=2\text{nm}$

2 states/well
=> 2 bands



$V_b=400\text{meV}$
 $W=10\text{nm}$, $B=2\text{nm}$

3 states/well
=> 3 bands



X States/Well => X Bands

$V_b=110\text{meV}$,
 $W=6\text{nm}$, $B=2\text{nm}$

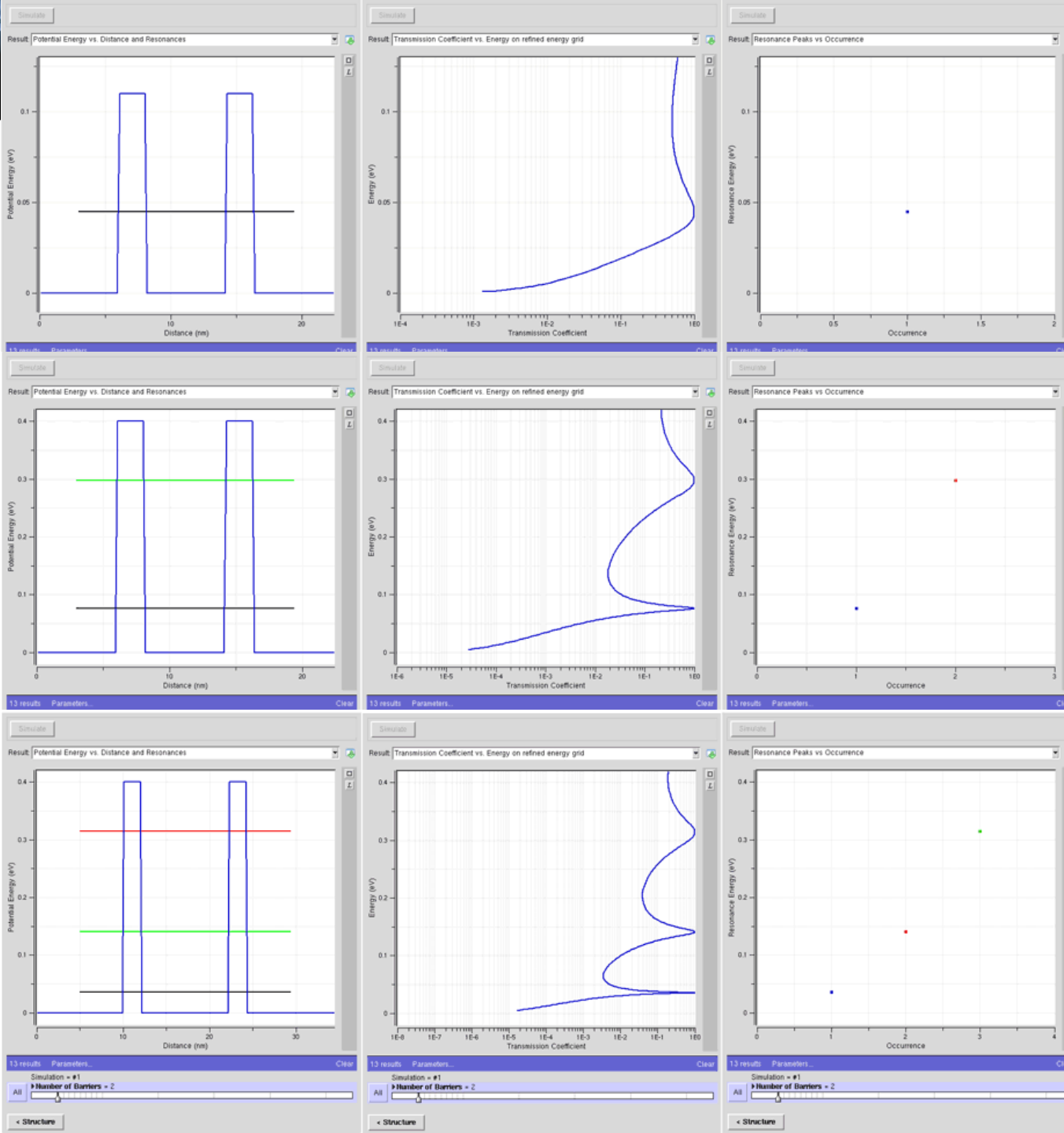
1 state/well
=> 1 band

$V_b=400\text{meV}$
 $W=6\text{nm}$, $B=2\text{nm}$

2 states/well
=> 2 bands

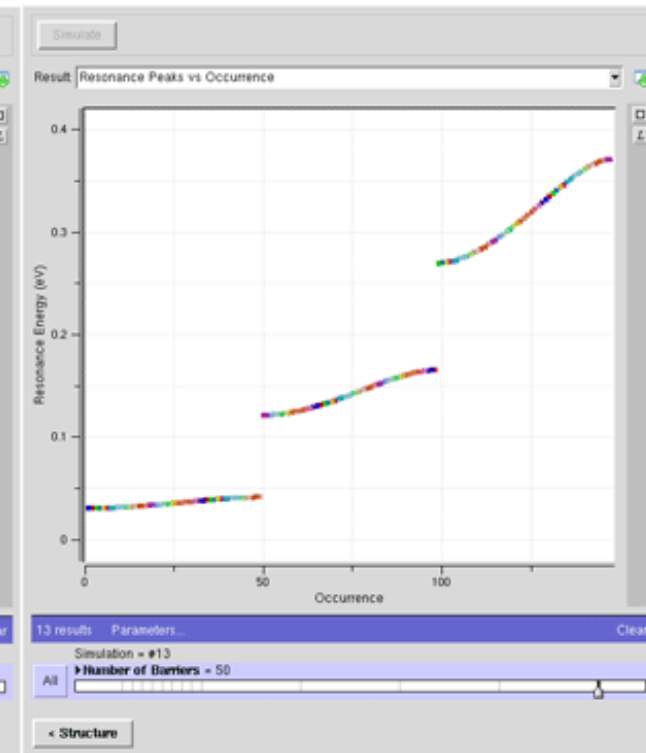
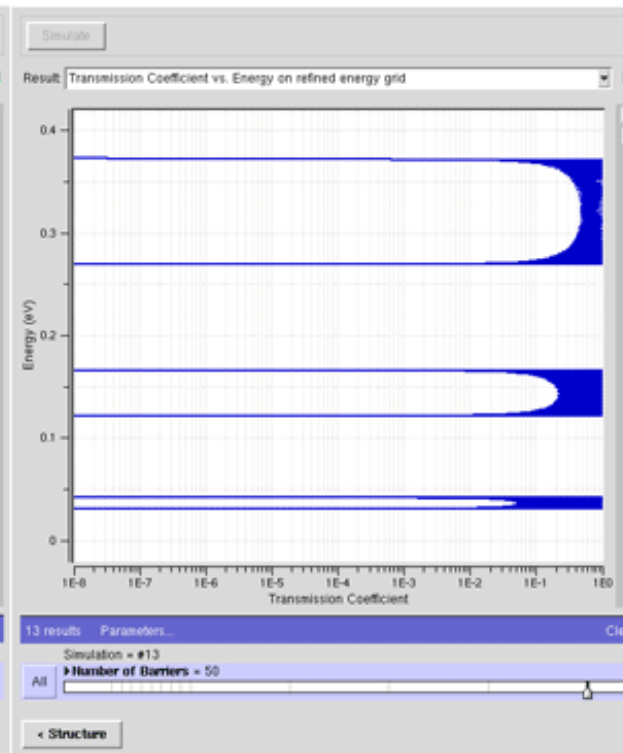
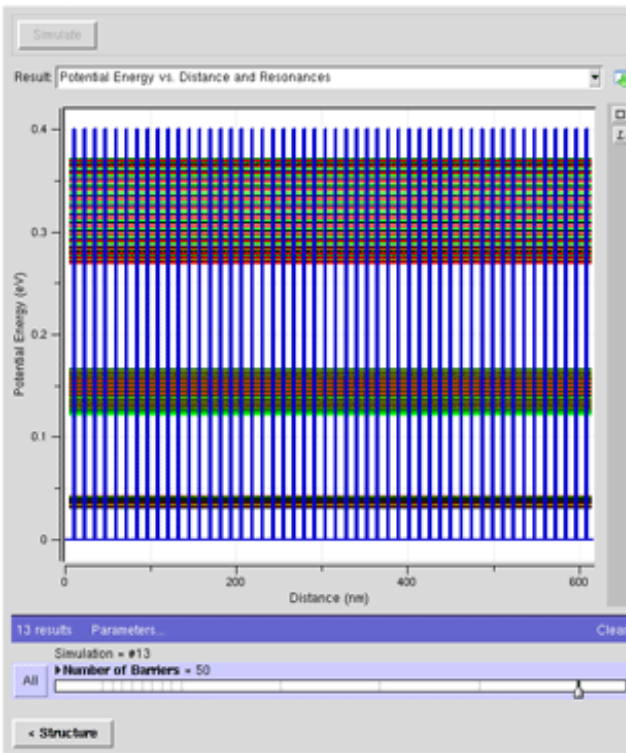
$V_b=400\text{meV}$
 $W=10\text{nm}$, $B=2\text{nm}$

3 states/well
=> 3 bands



Formation of energy bands

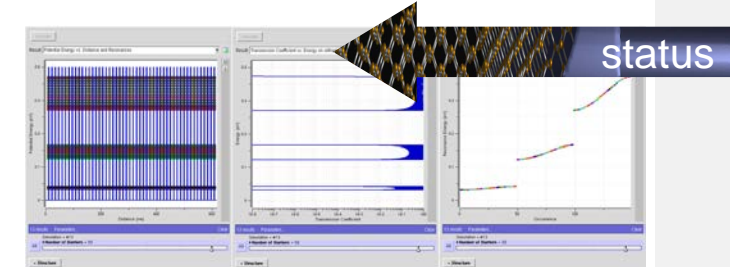
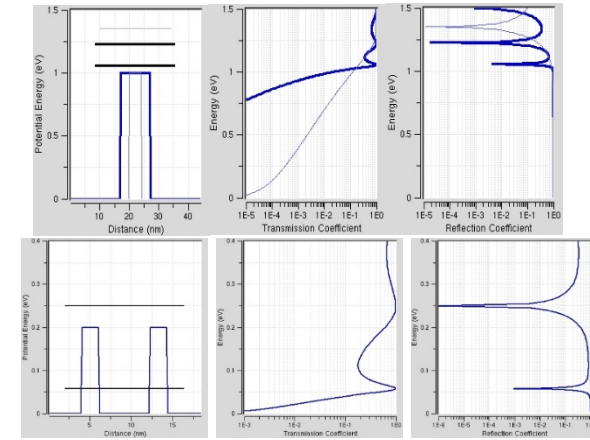
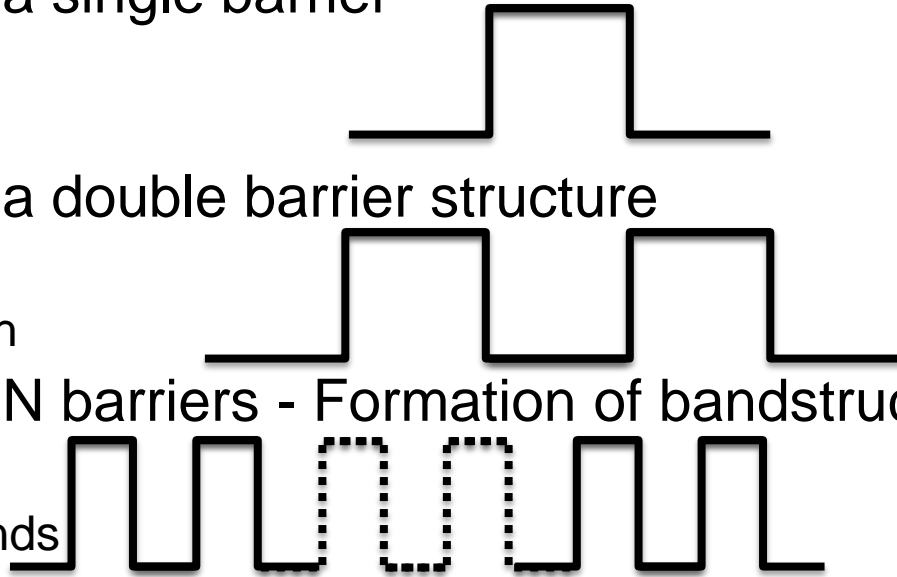
- Each quasi-bond state will give rise to a resonance in a well.
(No. of barriers -1)
- Degeneracy is lifted because of interaction between these states.
- Cosine-like bands are formed as the number of wells/barriers is increased
- Each state per well forms a band
- Lower bands have smaller slope => heavier mass



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- 6.3 Tunneling through a double barrier structure
 - » Resonant Transmission
 - » Transmission Peak Width
- 6.4 Tunneling through N barriers - Formation of bandstructure
 - » N wells – N Peaks
 - » S states per well – S Bands
- 6.5 Analytical and Numerical Solution Strategies



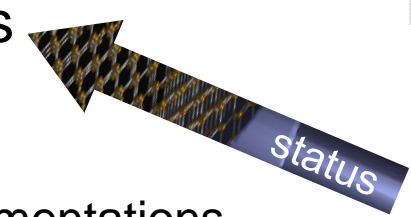
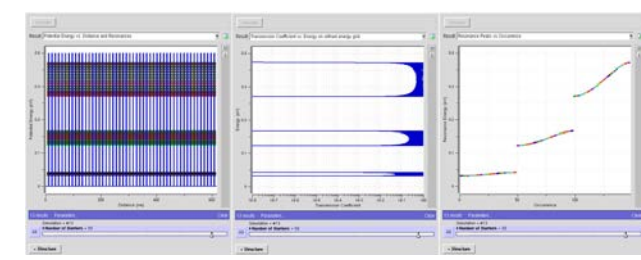
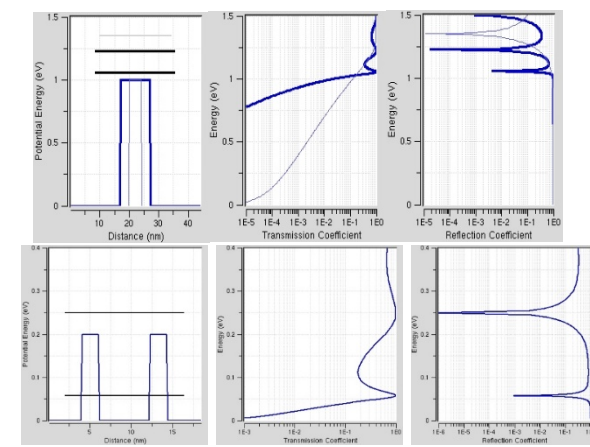
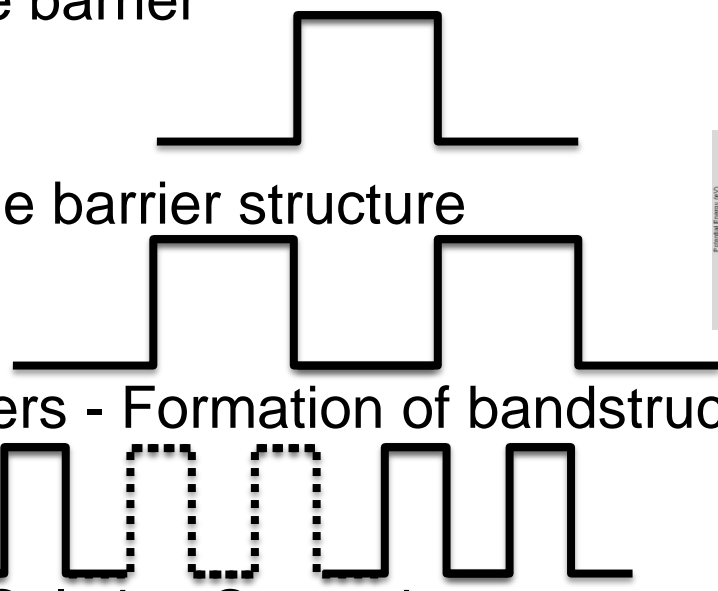
Reference:

piece-wise-constant-potential-barrier tool <http://nanohub.org/tools/pcpbt>

Section 6

Electron Tunneling - Emergence of Bandstructure

- 6.1 Transfer Matrix Method
- 6.2 Tunneling through a single barrier
 - » Analytical Solution
 - » Numerical observations
- 6.3 Tunneling through a double barrier structure
 - » Resonant Transmission
 - » Transmission Peak Width
- 6.4 Tunneling through N barriers - Formation of bandstructure
 - » N wells – N Peaks
 - » S states per well – S Bands
- 6.5 Analytical and Numerical Solution Strategies
 - » Analytical segmentation
 - » Transfer Matrix Method
 - » Discretizing Schrödinger's equation for numerical implementations



Reference:

piece-wise-constant-potential-barrier tool <http://nanohub.org/tools/pcpbt>