Photoluminescence excitation spectra in T-shaped quantum wires

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Outline
- About T-wire
- Experimental method and results
- Computational method
- Comparison and Discussion
# about "T-shaped quantum wire"

**quantum wire**
- quasi one-dimensional system
- interest on physics and application

**T-shape**
- 2-stepped growth of quantum well (cleaved edge overgrowth)
  → the intersection of them behaves as a quantum wire
20 T-wires (6nm x 14nm) are formed at the intersections of "Arm well" (6nm) and "Stem well"s (14nm)
Experimental method (PLE)

Excitation excited at: $\approx 7\, \mu W$

$\approx 4\, K$ (in cryostat)

by: tunable cw-TiS laser (resolution: 0.3 [meV])
# Experimental results (overview)

- Excitation power: $6.7 \mu W$
- Temperature: 3.7 K

Photon Energy [eV]

**PL Intensity (arb. units)**

- Core
- Cladding
- Stem well
- Arm well

* Typical optical anisotropy in both "Stem well" and "Arm well"

* Physics of quantum wire exists in pink region

PLE spectrum of T-wire sample
Experimental results (detail)

- 1D continuum state
\[ \propto E^{-\frac{1}{2}}(1D \text{DoS}) \]
suppressed by strong Coulomb interaction
Ogawa and Takagahara
PRB 43 14325 (1991)

- "1st excited state"
excitonic state of electron in 1st subband and hole in 2nd subband
Szymanska et al.
PRB 63 205317 (2001)
The computational method by Szymanska et al.

\[ \mathcal{H} = \mathcal{H}_e + \mathcal{H}_h + q \]

one-particle Hamiltonian of an electron and a heavy hole (effective mass approximation)

Coulomb interaction

diagonalized by the basis set of:

\[ \sum_{i,j,k} c_{i,j,k} \sin \left( \frac{z \pi}{L_z} k - \frac{\pi}{2} k \right) \chi_i^e(x_e, y_e) \chi_j^h(x_h, y_h) \]

plane wave in \( z \) axis

one-particle electron

one-particle heavy hole

\[ \mathcal{N}: \text{number of the states} \]

\[ z = z_e - z_h \]

relative axis

(and the energy of 1D-continuum and 2D exciton, also)
# comparison

[Graph showing PL intensity vs. photon energy]

- PL Intensity (arb. units)
- Photon Energy [eV]
- T-wire
  - x 1/5
- Arm well
  - core
  - cladding
# comparison

## Photoluminescence Intensity

<table>
<thead>
<tr>
<th>Photon Energy [eV]</th>
<th>PL Intensity (arb. units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.575</td>
<td></td>
</tr>
<tr>
<td>1.582</td>
<td></td>
</tr>
<tr>
<td>1.586</td>
<td></td>
</tr>
<tr>
<td>1.596</td>
<td></td>
</tr>
</tbody>
</table>

- **T-wire**
- **2Dexc (Arm)**
- **Arm well core**
- **1Dcon**
- **Cladding**

Photon Energy vs. PL Intensity (arb. units)
# comparison

![Graph showing PL Intensity (arb. units) vs. Photon Energy [eV]](image)

- **T-wire**
- **2Dexc (Arm)**
- **Arm well**

- **Plotted Peaks:**
  - 1Dcon
  - x 1/5
  - Cladding

- **Energy Points:**
  - 1.575 eV
  - 1.580 eV
  - 1.586 eV
  - 1.582 eV
  - 1.596 eV
  - 1.600 eV
<table>
<thead>
<tr>
<th>$x_e$</th>
<th>$y_e$</th>
<th>$x_h$</th>
<th>$y_h$</th>
<th>$x_e - x_h$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Wavefunction 1" /></td>
<td><img src="image2.png" alt="Wavefunction 2" /></td>
<td><img src="image3.png" alt="Wavefunction 3" /></td>
<td><img src="image4.png" alt="Wavefunction 4" /></td>
<td><img src="image5.png" alt="Wavefunction 5" /></td>
<td></td>
</tr>
</tbody>
</table>
ground state (no node)
# wavefunction (1 - 5)

2nd state (hole excited)
# wavefunction (1 - 5)

3rd state (exciton excited)
"excited hole" series
# wavefunction (1 - 5)

exciton Rydberg series
# comparison

![Graph showing comparison between T-wire and Arm well photoluminescence intensity.](image-url)
# comparison

![Graph showing PL intensity vs photon energy with T-wire, 2D excitation (Arm), 1D confinement (1Dcon), and cladding regions marked.](image-url)
# comparison

PL Intensity (arb.units)

Photon Energy [eV]

1Dcon

2Dexc

(Arm)

x 1/5

T-wire

Arm well

1 Arm well (binding energy) = 14 [meV]

PL Intensity (arb.units)

Photon Energy [eV]
**summary**

**conclusion**
- T-wire exciton ground state and 1D continuum states were separately observed.

- The oscillator strength of T-wire exciton ground state is very large, while the absorption of 1D continuum states is small. *(Nature of 1D system)*

- The binding energy of the T-wire exciton is 14 [meV]

- We attribute some small peaks to the exciton states consisting of excited hole subbands.

**future problem**
- A calculation in the form of Luttinger Hamiltonian
# probed region

**PL spectrum excited at 758[nm] (1.635[eV])**

![Graph showing PL spectrum with integrated region and energy scale from 1.568 to 1.576 eV]
Exactly calculated optical absorption spectra in 1D electron-hole system.

To avoid divergence of $E_b$, the potential $-\frac{e^2}{\epsilon(|z| + z_0)}$ is introduced.

Ogawa and Takagahara PRB 43 14325 (1991)

Sommerfelt factor $S_{1D} < 1$ --- specific in 1D system \( \text{cf. } S_{2D}, S_{3D} > 1 \)

\[
S = \frac{\text{absorption with Coulomb potential}}{\text{absorption without Coulomb potential}}
\]
# comparison

![Graph showing PL Intensity (arb. units) vs Photon Energy [eV].]

- **PL Intensity (arb. units)**
  - 1.600
  - 1.590
  - 1.586
  - 1.583
  - 1.575

- **Photon Energy [eV]**
  - 1.575
  - 1.582
  - 1.586
  - 1.596

- **T-wire**
- **2Dexc (Arm)**
- **Arm well**
- **1Dcon**
- **cladding**

- **core**
- **x 1/5**
- **3 5 9 16 27**

![Diagram labels and annotations for T-wire and Arm well regions.]
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# wavefunction (3, 5, 9, 16, 27)

exciton Rydberg series