Room-temperature excitonic absorption in quantum wires

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We measured absorption spectra of a T-shaped quantum wires at room temperature using waveguide-transmission spectroscopy. The one-dimensional exciton has the strong and narrow absorption peak with modal absorption coefficient of 160 cm$^{-1}$ and full width at half maximum of 7.2 meV. In addition, it shows strong polarization dependence.

Optical properties of quantum wires have been studied intensively toward novel device applications [1, 2]. So far, most researches have relied on emission measurements such as photoluminescence (PL) [3], PL excitation (PLE) [4–7], and there had been no quantitative direct absorption measurement on quantum wires. Recently, we measured absorption spectrum of a single T-shaped quantum wire (T-wire) embedded in an optical waveguide using straightforward waveguide-transmission spectroscopy at 5 K, and found that the one-dimensional (1D)-exciton ground state shows a large modal absorption coefficient of 80 cm$^{-1}$ in spite of the small lateral size of a T-wire, 14×6 nm [9]. The exciton peak showed thermal broadening at high temperatures, and room-temperature absorption was not measurable.

To investigate applicability of quantum wires to practical optical devices, room-temperature quantitative absorption measurement is very important. However, absorption spectrum of quantum wires at the room temperature has not been measured even by PLE.

In this letter, we report absorption spectra of 20 T-wires embedded in an optical waveguide at 297 K and 5K using waveguide-transmission spectroscopy. Because of increased overlap between the wires and the optical waveguide compared with the previous single-wire device, the 20-wire device has shown a strong absorption peak at the room temperature, demonstrating room-temperature 1D-exciton absorption. The 1D-exciton absorption peak has a maximum value of 160 cm$^{-1}$ and a full width at half maximum (FWHM) of 7.2 meV. In addition, the absorption by the T-wires has strong polarization anisotropy.

Figure 1 shows a schematic view of the 20-wire device fabricated using the cleaved-edge overgrowth method with molecular-beam epitaxy[10] and a growth-interrupt annealing technique[11]. The 20 T-wires are formed at T-shaped intersections of 20 multiple (001) Al$_{0.07}$Ga$_{0.93}$As quantum wells (stem wells) and a (110) GaAs quantum well (arm well). The T-wires are embedded in the core of the T-shaped optical waveguide (T-waveguide) with a lateral size of 1162×183 nm, surrounded by Al$_{0.5}$Ga$_{0.5}$As cladding layers. The cavity length $L$ is 512-μm, and cavity facets are uncoated. This sample is the same as that wires embedded in an optical waveguide at 297 K and 5K using waveguide-transmission spectroscopy. Because of increased overlap between the wires and the optical waveguide compared with the previous single-wire device, the 20-wire device has shown a strong absorption peak at the room temperature, demonstrating room-temperature 1D-exciton absorption. The 1D-exciton absorption peak has a maximum value of 160 cm$^{-1}$ and a full width at half maximum (FWHM) of 7.2 meV. In addition, the absorption by the T-wires has strong polarization anisotropy.

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Table I: Comparison of structures and measured data for the 20-wire and single-wire devices. The listed absorption data are for arm polarization. Peak area is evaluated as a product of peak value and FWHM. Ratio is evaluated for values (a) and (b).

<table>
<thead>
<tr>
<th>sample</th>
<th>20 wire</th>
<th>single wire</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-wire size (nm$^2$)</td>
<td>14×6</td>
<td>14×6</td>
<td>1</td>
</tr>
<tr>
<td>Waveguide size (nm$^2$)</td>
<td>1162×183</td>
<td>514×127</td>
<td>9.3</td>
</tr>
<tr>
<td>confinement factor $\Gamma$</td>
<td>4.3×10$^{-3}$ (a)</td>
<td>4.6×10$^{-4}$ (b)</td>
<td></td>
</tr>
<tr>
<td>temperature (K)</td>
<td>297</td>
<td>5</td>
<td>9.4</td>
</tr>
<tr>
<td>coupling efficiency $\eta$</td>
<td>0.40</td>
<td>0.40</td>
<td>0.24</td>
</tr>
<tr>
<td>continuum $\alpha$ (cm$^{-1}$)</td>
<td>150 (a)</td>
<td>16 (b)</td>
<td></td>
</tr>
<tr>
<td>exciton peak $\alpha$ (cm$^{-1}$)</td>
<td>160</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>FWHM (meV)</td>
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<td>&lt;2</td>
<td>1.6</td>
</tr>
<tr>
<td>peak area (cm$^{-1}$meV)</td>
<td>1152 (a)</td>
<td>128 (b)</td>
<td></td>
</tr>
<tr>
<td>peak energy (eV)</td>
<td>1.4884</td>
<td>1.5808</td>
<td></td>
</tr>
</tbody>
</table>

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FIG. 1: A schematic view of the 20-wire device. Percentages in parentheses represent the Al content of Al$_x$Ga$_{1-x}$As.
Upper columns in Table I summarize structural parameters of the 20-wire device, in comparison with those of the single-wire device used in previous study [9]. The size and constituent elements of individual T-wire are the same in both devices. On the other hand, those of the T-waveguide is different. By increasing the number of T-wire, optical confinement factor $\Gamma$ of the 20-wire device is larger than that of the single-wire device by a factor of 9.3, which is important comparing material absorption coefficients between two devices in latter discussion.

The experimental method of waveguide-transmission spectroscopy is the same as before [9] in both temperatures, except for using two linear polarizations parallel to the arm well (denoted as arm polarization) and parallel to the stem well (stem polarization). The coupling efficiency $\eta$ between incident light and T-waveguide is 0.4 in both temperatures.

Figure 2 shows absorption spectra for 20 wires at 297 K. A longitudinal axis represents a modal absorption coefficient $\alpha$. The solid and dotted curves represent absorption for arm and stem polarizations, respectively. As will be explained later, the absorption peak at 1.4884 eV for arm polarization is due to 1D-exciton ground state. The absolute value of the absorption coefficient for the 1D exciton is the most important result in this paper. The value of $\alpha=160$ cm$^{-1}$ gives the transmittance without reflection $e^{-\alpha L}=2.8 \times 10^{-4}$ when $L$ is 512 $\mu$m. This demonstrates that the quantum wires in an optical waveguide has a strong excitonic absorption for the light propagating along the wires even at room temperature, in spite of the small optical confinement factor which is about one order of magnitude smaller than those of ordinary multiple-quantum-well devices.

The 1D-exciton peak at 1.4884 eV is indicated by the dotted vertical line in Fig. 2. This peak is broad at the higher energy side. Thus, FWHM of the peak is estimated as 7.2 meV from half FWHM of 3.6 meV at the lower energy side. This value is smaller than those of the quantum wells or the quantum dots at room temperature [12], though we are not aware of the reason at the present time.

The polarization dependence of absorption spectrum for stem polarization has no peak structure. The difference of absorption coefficient between two polarizations is 145 cm$^{-1}$ at 1.4884 eV, which corresponds to $e^{-\alpha L}=6.0 \times 10^{-4}$. Stronger absorption for arm polarization indicates that the T-wires have the similar polarization dependence of the arm well [12]. This characteristic originates from the strong quantum confinement in the direction of [110].

These three experimental results on 1D excitonic absorption indicate the potential applications of quantum wires to various optical devices like modulators, switches, and amplifiers.

Figure 3 shows absorption spectra for the 20 wires at 5 K, which help us understanding in detail room-temperature absorption. The solid and dotted curves correspond to absorption spectra for arm and stem polarizations, respectively.

The line shape of absorption for arm polarization agrees well as that of single-wire device [9], and we are able to assign each peak of the 1D-exciton ground state, the first excited state of the 1D exciton, and the 1D continuum states, as denoted in the figure. The increasing of absorption above 1.598 eV is due to the exciton in the arm well.

The polarization dependence for each absorption peak is clearly resolved. Absorption of 1D exciton and continuum states decrease drastically in stem polarization. The excited exciton, on the other hand, has similar absorption value for both polarizations. This difference in polarization dependence originates from the difference of the hole.
In this experimental setup, we were not able to estimate the absorption coefficient above 200 cm$^{-1}$ because of small transmission light. Although the peak value of 1D exciton for arm polarization is above detection limit, the FWHM is estimated under 2 meV from that in stem polarization or that of excited exciton. This indicates high uniformity of the 20 T-wires in the whole region. Therefore, FWHM for 1D exciton at 297 K is not affected by the inhomogeneity of 20 T-wires.

Absorption coefficient of the continuum states for arm polarization is about 150 cm$^{-1}$. This value is 9.4 times larger than that of the single-wire device, 16 cm$^{-1}$, whose ratio corresponds to that of the optical confinement factor $\Gamma$ as shown in Table I. This result demonstrates that material absorption coefficient normalized by $\alpha/\Gamma$ must be the same in both 20-wire and single-wire devices.

We are convinced that the absorption peak for arm polarization at 297 K is attributed to 1D-exciton ground state, because we confirmed experimentally that 1D-exciton peak at 5 K in Fig. 3 change to the peak at 297 K in Fig. 2 continuously increasing temperature.

We explain further details about above assignment. Lower columns in table I aligns the absorption data of 20-wire device at 297 K and 5 K, and of a single-wire device at 5 K for arm polarization[9]. The area of absorption coefficient for 1D-exciton peak should be conserved in both 297 and 5 K[?], though FWHM increases with increasing temperature. The peak area at 297 K is about evaluated from the product of its peak value and FWHM. Although we were not able to measure the peak value for 20-wire device at 5 K, we know the value for single-wire device. The product for 20-wire device at 297 K is 9 times larger than that for single-wire device at 5 K. Thus, the area of material absorption coefficient $\alpha/\Gamma$ is almost the same in both temperatures.

Furthermore, the energy difference of the peaks between 297 and 5 K is 92.4 meV. This value is close to the band gap energy shift of 95 meV for bulk Al$_x$Ga$_{1-x}$As ($x \leq 0.45$) between two temperatures[14]. These facts make sure that the absorption peak at 297 K in Fig. 2 is due to 1D-exciton ground state.

In summary, we measured absorption spectra of 20 T-wires embedded in an optical waveguide at room temperature using waveguide-transmission spectroscopy. The 20 T-wires have room-temperature 1D-exciton absorption peak with the maximum value of 160 cm$^{-1}$ and FWHM of 7.2 meV. In addition, it has strong polarization anisotropy.

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