In quantum wires, one-dimensional (1D) excitons are expected to have a large binding energy, and large oscillator strength in the ground state, while the oscillator strength of exciton excited states and 1D continuum states should be suppressed.

The absorption line shape of the 1D continuum states was recently measured in a photoluminescence-excitation (PLE) spectrum of T-shaped quantum wires (T-wires) with improved homogeneity, which were fabricated by cleaved-edge overgrowth with growth-interrupt annealing in molecular-beam epitaxy. The results did indeed show reduced absorption of the continuum states, and qualitatively support a simple model calculation. On the other hand, some excited-exciton states that were predicted in a more detailed calculation for the T-wire geometry were not found in the observed spectrum. This seems to indicate an inconsistency between the experiment and the theory concerning the above fundamental effect, which must be solved before this effect can be applied to optical devices such as quantum wire lasers.

In this work, we demonstrate PLE spectroscopy of highly uniform T-wires in an improved optical configuration that allows us to measure polarization-dependent PLE spectra with less scattering-light noise than before. The observed spectra of the T-wires exhibit small isolated peaks, found to be in good agreement with the excited-exciton states predicted in the calculation. The peak assignments are supported by the polarization-dependence of the PLE spectra.

We studied several samples that had a nominally identical T-wire-laser structure containing 20 T-wires formed at 20 T-wire-laser structure containing 20 T-wires formed at 20 periods of 14 nm Al0.07Ga0.93As quantum wells (stem wells) and a 6 nm GaAs quantum well (arm well), as schematically shown in Fig. 1. The barrier layers in the core and cladding regions had different Al concentrations, 35% and 50%, respectively, so the arm wells in the core and cladding regions had slightly different energies. Details of the structure and fabrication method are presented elsewhere. The configuration for optical excitation and detection is also shown in Fig. 1. The excitation was performed via a 0.5 numerical aperture objective lens through a (110) GaAs surface using a continuous-wave titanium-sapphire laser at an input power of 6.7 μW (Fig. 1) or 2.4 μW (Fig. 2). The excitation light had polarization perpendicular (\( \perp \)) or parallel (\( // \)) to the T-wires. In order to eliminate intense backward scattering of the excitation light, photoluminescence (PL) from the sample was collected via a (110) surface.

Figure 1 shows PLE spectra for perpendicular (\( \perp \)) and parallel (\( // \)) polarizations at 5 K. Large peaks denoted “HH” and “LH” are due to 2D heavy-hole and light-hole excitons in the stem wells, and they demonstrate the typical polarization anisotropy of (001) GaAs quantum wells. The two peaks denoted “core” and “cladding” are due to 2D heavy-hole excitons in the core arm well on 35% barrier and the cladding arm well on 50% barrier, respectively, which were confirmed by a separate PL imaging experiment. In those peaks, optical anisotropy exists due to the crystallographic anisotropy of a (110) GaAs quantum well. The lowest energy peak is due to the 1D ground-state excitons in the T-wires. The PLE spectrum for the parallel polarization reproduces our previously reported spectrum.

Figure 2 shows PLE spectra for perpendicular (\( \perp \)) and parallel (\( // \)) polarizations at 5 K measured in detail around the low energy region in Fig. 1. The strong peak at the lowest energy (1.575 eV) shown in both the spectra is due to 1D ground-state excitons in the T-wires. Between this peak and the 2D arm-well exciton peak, continuous absorption with an onset at 1.586 eV is observed for parallel polarization, while small peaks are observed at 1.582 and 1.586 eV (7 and 11 meV above the ground-state-exciton peak) in perpendicular
The polarization of the light used for excitation in PLE was perpendicular (\(\perp\)) or parallel (\(\parallel\)) to the T-wires. The polarization together with the continuous absorption above 1.586 eV. The origins of the small peaks is most likely the excitation of the ground-subband and hole excited-subbands, for the peaks showing strong polarization dependence. The continuous absorption band is expected to correspond to the 1D continuum states. A detailed discussion will now be given comparing a data with a theoretical calculation.

We performed a model calculation of a single electron-hole pair, or an exciton, in the present 14 nm \(\times\) 6 nm T-shaped geometry using a formulation reported previously. Our model assumes a single hole band corresponding to the ground hole subband in the arm well, which has an anisotropic effective mass due to the band-mixing effects\(^{11,24,25,26,27}\). Additional band-mixing effects due to lateral confinement is neglected, since the second hole subband in the arm well is deviated over 30 meV. Calculated results are accurate in the low energy region of our interest. The calculation is based on exact diagonalizations of Coulomb interaction matrix elements, which gives energy eigenvalues \(E_n\) and electron-hole envelope wavefunctions \(\Psi_n(x, y, z)\) \((n = 1, 2, 3, \ldots)\) of not only the ground but also the excited states of the exciton system. Here, \((x_e, y_e, z_e)\) and \((x_h, y_h, z_h)\) denote the positions of an electron and a hole. The method of the calculation is the conjugate-gradient minimization\(^{25}\) in a coordinate where \(x_e, y_e, x_h\) and \(y_h\) move within 42 nm length, and \(z\) goes from -50 nm to 50 nm. Since we use a dense grid, the results are well converged. Though results for low-energy confined states are accurate, care must be taken over results for high-energy states which are not accurate, because of the extension in the finite sized box and the mixing effect of high energy bands. Thus, the energies of 2D exciton states in the arm well and 1D continuum states in the T-wires were calculated by another method.

The oscillator strength of the \(n\)-th state was evaluated as \(\frac{1}{4\pi} \int \int dxdy|\Psi_n(x, y, x, y, 0)|^2\), a square of an integral of an electron-hole wavefunction with respect to the same electron and hole positions. This evaluation is justified for wavefunctions spatially smaller than the wavelength of light in conventional far-field optical detections. In a previous paper\(^{15}\), oscillator strength was evaluated as \(\frac{1}{4\pi} \int \int dxdy|\Psi_n(x, y, x, y, 0)|^2\), which is applicable for a particular detection via a local probe in a near-field scanning optical microscope. Such "local-probe oscillator strength" is not used in the present analysis.

For comparison with experimental data, we added an offset energy of 1.521 eV (corresponding to the bulk GaAs band-gap energy) to \(E_n\), and plotted the calculated oscillator strengths of the \(n\)-th states by circles in Fig. 2. The energies of the 1D continuum states and the arm-well 2D-exciton states are shown by dashed lines. The calculated energy of the \(n=1\) state with large oscillator strength and the 2D exciton energy in the arm well both show good agreement with the measured strong PLE peaks of the T-wire excitons at 1.575 eV and the arm well excitons at 1.596 eV. Though the oscillator strength of the \(n=3\) state is zero, those of the \(n=2\) and 4 states have
finite small values. The calculated energy positions as well as the small oscillator strength of the $n=2$ and 4 states show good agreement with the measured small PLE peaks at 1.582 and 1.586 eV.

Figure 3 shows wavefunctions $\Psi_n(x_e, y_e, x_h, y_h, z = z_e - z_h)$ for $n=1,5$ and 16, where $|\Psi_n|^2$ for various parameter pairs are plotted in the way described in the previous paper. The wavefunction for the $n=1$ state has no node against any parameter axis. It is well confined in the T-wire and demonstrates that the $n=1$ state is the ground-state exciton in the T-wire. This confirms that the observed strong PLE peak at 1.575 eV is due to the ground-state exciton in the T-wire.

For $n=2$ and 4, wavefunctions have no node in the electron $(x_e, y_e)$ motion and the electron-hole relative $z$ motion, while nodes appear in the hole $y_h$ motion, which show that the $n=2$ and 4 states are exciton states consisting of the electron ground subband and the hole excited subbands. Errors in the calculated energy eigenvalues of these excited states in the finite-sized-box are small, because of the heavy effective mass of hole. The oscillator strengths of these states are small, but not zero, because wavefunctions for different subbands of electrons and holes are approximately orthogonal. The calculated energy and oscillator strength of these states agree well with the experimentally observed two small peaks at 1.582 and 1.586 eV.

Since the present calculation assumes a single hole band, it does not evaluate absolute values of polarization-dependent absorption intensities. However, different hole subbands in general cause different polarization-dependence. Thus, different hole subbands contained in the $n=1, 2, 4$ states qualitatively explain the experimental finding that the two peaks at 1.582 and 1.586 eV show stronger absorption for perpendicular polarization, unlike the ground-state exciton peak.

For $n=3, 5, 16$, wavefunctions have no node for the electron $(x_e, y_e)$ motion and the hole $(x_h, y_h)$ motion, while nodes appear in the electron-hole relative $z$ motion, which show these states are 1D-exciton excited states consisting of the electron ground subband and the hole ground subband in the T-wire. The $n=3$ wavefunction is an odd function of $z$ and has vanishing oscillator strength, whereas the $n=5$ and 16 wavefunctions are even functions of $z$ and have large oscillator strength. We should note here that all these states have extended wavefunctions for $z$, for which the calculated oscillator strength and energy eigenvalues are not accurate because of the finite-sized-box and the light effective mass of electron, and cannot be compared directly with the experimental spectrum. In fact, the separately calculated onset of 1D continuum states is at 1.589 eV, and all the exciton bound states including the $n=5$ and 16 states should be below this energy.

An important point we learn for these states is that these 1D-exciton excited states with even parity consisting of the electron ground subband and the hole ground subband in the T-wire have dominant oscillator strength, while other excited states have only negligible oscillator strength. On the basis of this qualitative point, the experimentally observed continuous absorption band around 1.589 eV is ascribed to excited exciton states and 1D continuum states consisting of the electron ground subband and the hole ground subband in the T-wire.

The similarity in polarization dependence between the continuous absorption band and exciton ground state suggests that the contributing hole subband is common.

In summary, we measured polarization-dependent PLE spectra of highly uniform T-wires, and found good agreements with a model calculation. The lowest energy peak due to the 1D-exciton ground state and a continuous absorption band due to 1D continuum states show polarization dependence similar to each other, while two small peaks due to excited hole subbands have different polarization anisotropy. The oscillator strength of the exciton ground state in T-wires is very large, in stark contrast with the small oscillator strength of the excited exciton states and the 1D continuum states. Inverse-square-root singularity was absent in the absorption line shape of 1D continuum states in agreement with theories.

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FIG. 3: Contour-plots of calculated $|\Psi_n|^2$ for $n=1, 2, 3, 4, 5$ and 16 for various parameter pairs. Parameters $(x_e, y_e, z_e)$ and $(x_h, y_h, z_h)$ denote the positions of an electron and a hole, and $z$ is defined by $z = z_e - z_h$. The directions of $x, y$ and $z$ correspond to [110], [001], and [110]. The size of the boxes is 42 nm $\times$ 42 nm for the upper two rows, 84 nm $\times$ 84 nm for the third row, and 84 nm $\times$ 100 nm for the bottom row. The three contour lines in each box represent 80%, 50%, and 20% lines of maximum. In the relative $xy$ coordinate system, since $|\Psi_n|^2$ is plotted for $z$ relative = 0, it is zero everywhere in the $n=3$ state which has a node at $z = 0$.  

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