Strong photo-absorption by a single quantum wire in waveguide-transmission spectroscopy

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We report direct absorption measurement of a single T-shaped quantum wire by waveguide-transmission spectroscopy at 5 K. One-dimensional exciton in the ground state has a single absorption peak, which indicates high uniformity of our quantum wire in the whole cavity region. The absorption coefficient at the peak is 84 cm⁻¹ despite the single quantum wire.

Quantum wire structures have attracted much attention due to the singularity of the joint density of states at the energy of the band edge. One of the interesting properties of quantum wire structures is that excitonic effects are enhanced compared to those of quantum well and bulk materials, which should remarkably appear in the photo-absorption spectra near the band edge.

The pathological features of excitonic absorption in ideal one-dimensional (1D) system, namely, infinitesimal wire cross section and perfect confinement, has been clarified[1]. Recently, quantum wire lasers consist of GaAs/AlGaAs have been realized[2, 3], and there are some interesting theoretical studies about excitonic absorption in such realistic 1D systems[4–6]. Not only from the interest in 1D physics but also from the expectation of potential applications to optical devices[7, 8], it is important to know the absolute value of 1D excitonic absorption.

However, there is no report of direct absorption measurement on quantum wires. Because highly uniform quantum wire could not be fabricated and transmission experiment is very difficult due to their small volume.

T-shaped quantum wire (T-wire) fabricated using cleaved-edge overgrowths with molecular-beam epitaxy has highest uniformity of 1D structure because we created a new growth-interrupt annealing technique[9]. Therefore, single-mode lasing from the ground state in a single T-wire was observed under optical pumping[10]. The line shape of absorption in the T-wire have been investigated by photoluminescence excitation (PLE) measurements[11]. It revealed that the three absorption peaks near the band edge were attributed to 1D-exciton ground state, 1D-exciton excited state, and 1D-continuum states respectively. Our motivation is to know the absolute value of absorption coefficients for these states, especially 1D-exciton ground state, which can not be demonstrated by PLE.

Transmission spectroscopy using optical waveguide would be good to measure directly the absorption for nanostructures like quantum wires because of long interaction length between the light and medium[12]. Furthermore, it would be more important to investigate the optical characteristic of the new waveguide-devices.

In this letter, we report the direct absorption measurement on a single T-wire by microscopic waveguide-transmission spectroscopy. We obtained absorption spectrum of the T-wire near the band edge for the light

![FIG. 1: Schematic views of cross section for the single T-wire laser and transmission experiment. Percentages mean Al content of AlₓGa₁₋ₓAs for each layer. T-shaped intersection of an arm well and a stem well form a single T-wire. The contour lines show constant probability for electrons confined in a T-wire (|ψ|² ∼ 0.2 ~ 1.0). A big solid arrow and dashed arrows indicate the incident light and the transmitted light.](image-url)
propagating along a wire at 5K. Absorption of T-wire is strong for [001] polarization. The full width half maximum (FWHM) of spectral peak for 1D-exciton ground state is 1.6 meV and the peak intensity is 84 cm$^{-1}$ despite a single T-wire.

Figure 1 shows a schematic views of our single T-wire laser sample and microscopic waveguide-transmission measurement. The single T-wire is formed at a T-shaped intersection of a (001) quantum well (stem well) and a (110) quantum well (arm well). The size of the T-wire is 6 nm x 14 nm. The T-wire is embedded in the core of a T-shaped optical waveguide that consists of 514-nm-thick (001) layers (mainly Al$_{0.35}$Ga$_{0.65}$As) and 127-nm-thick (110) layers (mainly Al$_{0.1}$Ga$_{0.9}$As) with surrounding Al$_{0.5}$Ga$_{0.5}$As cladding layers. The cavity length of the laser is 500 µm and cavity facets are uncoated. The fabrication process and lasing properties of the single T-wire laser were previously reported[10]. The emission pattern from the T-waveguide corresponding to the lowest waveguiding mode was characterized[13].

Calculated optical confinement factor $\Gamma$, defined as the overlap portion between the lowest waveguiding mode and a T-wire, by a finite element method with background refractive index is about 4.62 × 10$^{-4}$. Though this is very small, we could obtain the absorption spectrum when using waveguide-transmission measurement.

The sample was attached to a copper block in the cryostat with 10$^{-6}$ torr and cooled down to 5 K. Variable continuous-wave titanium-sapphire laser was used as transmission light. The laser polarization was set parallel to the arm well. Transmission light was chopped into a 1% duty ratio to minimize sample heating and spatially filtered to improve its quality. After passing a polarizer, the beam was focused by a 0.5 numerical aperture objective lens with 10 mm focal length to about 1 µm radius on a cavity facet, and directly coupled into the T-waveguide with intensity $I_0(\lambda)$ (a big arrow in Fig. 1). Thus, the both directions of the transmission light and the quantum wire are [110]. The transmitted light from the other cavity facet (a big dashed arrow) was collected by the same objective lens as above. After passing a polarizer, it was coupled by a achromatic lens into a single core fiber with 50 µm aperture, which prevents the background light which has not been propagated in the T-waveguide to be detected. Thus, the intensity of transmitted light from only the T-waveguide was measured as $I(\lambda)$ by liquid-nitrogen-cooled CCD system. We obtained transmittance $T(\lambda) = I(\lambda)/I_0(\lambda)$ at any wavelength.

Figure 2(a) shows transmittance spectrum in the single T-wire around the band edge. The number of measurement points is about 1000. Strong attenuation around 1.583 eV is caused by the absorption of 1D-exciton ground state. Below this energy, there is no absorption by T-wire, instead Fabry Perot fringes with 0.137 maximum transmittance arise from reflections and interference effects. This oscillation is

$$T(\lambda) = \frac{(1 - R)^2 \eta e^{-\alpha L}}{(1 - Re^{-\alpha L})^2 + 4Re^{-\alpha L} \sin^2 \delta(\lambda)/2}, \quad (1)$$

where $R$ is reflectance, $\eta$ coupling efficiency to T-waveguide, $\alpha$ modal absorption coefficient, $L$ cavity length, and $\delta(\lambda)$ is the phase contrast corresponding to resonator, respectively. The oscillation term in equation (1) is 0 at the energy of maximam transmittance, and equation (1) reduced to

$$T_{\text{max}} = \frac{(1 - R)^2 \eta e^{-\alpha L}}{(1 - Re^{-\alpha L})^2}. \quad (2)$$

Refractive index for the lowest waveguiding mode is introduced as 3.38 by the above mode calculation. The absorption value below 1D exciton ground state is introduced as 4.4 cm$^{-1}$ (internal loss) by Hakki & Paoli method i.e., $T_{\text{min}} = \frac{(1 - Re^{-\alpha L})^2}{(1 - Re^{-\alpha L})^2}$[14]. Substituting these values to equation (2), the coupling efficiency is introduced as about 0.2. In the region of apparent oscillation, transmittance over 10$^{-4}$, we derive the absorption

![Figure 2(a) The transmittance spectrum of the single T-wire for the light polarized parallel to the arm well at 5 K, Y axis is log scale. (b) The absorption spectrum of the single T-wire. Three peaks correspond to 1D-ground-state exciton, 1st excited exciton, and continuum states.](image)
coefficients from equation (2) using measurement points of just maximum transmittance. In the other region, we also use equation (2) for all measurement points, because oscillation term is negligible for large absorption.

Figure 2(b) shows absorption spectrum of single T-wire laser. The Y axis means modal absorption coefficient including internal loss of 4.4 cm\(^{-1}\). Surprisingly, the line shape of absorption spectrum agrees well with that of PLE spectrum\[11\]. Thus, three spectral peaks indicated by big solid arrows are assigned as follow: spectral peak at 1.5827 eV due to 1D-exciton ground state, at 1.5900 eV due to 1D-exciton excited state consisting of an electron in ground state and a hole in excited state, above 1.5940 eV due to 1D-continuum states. The increased absorption above 1.6010 eV is due to the arm well whose absorption is over the detection limit, 200 cm\(^{-1}\).

We describe the three crucial things on the reliability of the experiment. Firstly, We assume that coupling efficiency \(\eta\) in Eq. (2) is constant in all energy. The great care was, therefore, taken in the laser path, any vibration of experimental setup, and temperature movement of the sample, so that the transmission light coupled to the T-waveguide with the highest efficiency. The validity of above assumption is confirmed from that the absorption value derived by Hakki & Paoli method, which is independent on \(\eta\), is almost the same as that in Fig. 2(b). Experimental error is estimated as about 2 cm\(^{-1}\) from the fluctuation of absorption around 1.575 eV. Secondly, if light coupled to higher order waveguiding modes could be, to eliminate such light could be impossible in using the single core fiber as shown in Fig. 1 and detection of it would become measurable background. Because their mode have intensity minimum at the T-wire and would be weakly absorbed in the T-wire. So we investigated the mode structure of transmitted light on the [110] surface by microscopic imaging method\[13\]. In result, only a lowest order mode was observed in all energy. Thirdly, the saturation of excitonic absorption for 1D-exciton ground state occur above \(I_0\) of 440 nW. Thus, \(I_0(\lambda)\) was set to 180 nW or less to avoid saturation of absorption.

The absorption peak of 1D-exciton ground state has single structure with FWHM of 1.6 meV. The small additional peak around 1.5858 eV (dashed arrow) is due to the quantum wire consisting of 1 monolayer thinner arm well\[15, 16\]. All these features demonstrate unprecedentedly high uniformity of our single quantum wire in the whole cavity region. The absorption value of 84 cm\(^{-1}\) at the 1D-ground-state exciton peak corresponds to the transmittance of 1.5 \% for the 500 \(\mu\)m-length waveguide. Quantum wires are often considered not suitable for optical devices due to their small volume. However, this data demonstrates that the single wire in the waveguide has much absorption at the energy of 1D-exciton ground state for the light propagating along the wire.

Absorption of continuum states is much smaller than 1D-exciton ground state, in which inverse-square-root singularity at the band edge is absent as theoretically predicted\[4\]. This fact supports that coulomb correlation would be important in the quantum wire\[17\].

The absorption of T-wire for the light parallel to the stem well ([110]) is very weak. We will report the polarization dependence in next paper.

In summary, we successfully measured the absolute value of absorption for the single T-wire at 5 K. The waveguide-transmission measurement is available to investigate absorption for nanostructures, like a quantum wire. 1D-exciton ground state has a single absorption peak with FWHM of 1.6 meV, which demonstrates high uniformity of our single T-wire in the whole cavity region. The absorption coefficient at the peak is 84 cm\(^{-1}\) despite a single wire.

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FIG. 3: Schematic views of cross section for the single T-wire laser and transmission experiment. Percentages mean Al content of Al$_x$Ga$_{1-x}$As for each layer. T-shaped intersection of an arm well and a stem well form a single T-wire. The contour lines show constant probability for electrons confined in a T-wire ($|\psi|^2 = 0.2 \sim 1.0$). A big solid arrow and dashed arrows indicate the incident light and the transmitted light.

FIG. 4: (a) The transmittance spectrum of the single T-wire for the light polarized parallel to the arm well at 5 K. Y axis is log scale. (b) The absorption spectrum of the single T-wire. Three peaks correspond to 1D-ground-state exciton, 1st excited exciton, and continuum states.