# Laterally Squeezed Excitonic Wave Function in Quantum Wires

T. Someya,[1] H. Akiyama,[1,2] and H. Sakaki[1]

[1]*Research Center for Advanced Science and Technology, University of Tokyo and Quantum Transition Project, Research Development Corporation of Japan, 4-6-1 Komaba, Meguro-ku, Tokyo, Japan*

[2]*Precursory Research for Embryonic Science and Technology, Research Development Corporation of Japan, Honcho 2-45-13, Nakano-ku, Tokyo, Japan*

(Received 29 December 1994)

Photoluminescence spectra are systematically studied at 4.2 K on a series of high-quality T-shaped edge quantum wires (QWRs) whose linewidths are as small as 4–7 meV. By measuring spectra in magnetic fields up to 12 T and comparing them with those of quantum wells (QWs), the effect of lateral confinement on exciton wave functions in QWRs is clearly and quantitatively demonstrated. It is found in QWRs formed by intersecting 5 nm thick GaAs QWs that the wave function of a one-dimensional (1D) exciton is squeezed far below the minimum size that has ever been realized by any 2D excitons in GaAs QWs.

PACS numbers: 73.20.Dx, 78.66.Fd

The spatial overlap of electron-hole wave functions is enhanced in quantum wells (QWs) due to quantum confinement and enhanced electron-hole Coulomb interaction. The well-known room temperature excitonic absorption [1] and the enhancement of optical transition probability in QWs are caused by this enhanced overlap of wave functions. Quantum wires (QWRs) are attracting increasing interest, as the wave functions further compressed by lateral confinement may lead to a substantial enhancement of the optical transition probability, which is a challenge in wave function engineering.

The lateral size of electron-hole wave functions or excitons can be evaluated by studying the energy shift of photoluminescence (PL) under a magnetic field (diamagnetic shift). To probe into the lateral confinement effect in QWRs, however, it is essential to compare their diamagnetic shifts with those of QWs having the same normal thickness, since the Coulomb interaction enhanced by the confinement in the normal direction has already reduced the diamagnetic shift of two-dimensional (2D) excitons in QWs. We have to note that the Bohr radius of 2D excitons decreases substantially when the well thickness $L_w$ is reduced, especially down below 10 nm [2].

Although the diamagnetic shift was studied in several different QWRs, this point was missing in the previous reports [3–7]. In some work [3,4,6], the lateral confinement is quite weak, and the measured diamagnetic shifts were almost the same as that of 2D excitons in QWs. In other cases [5,7], where the confinement was strong, the PL linewidth or the fluctuation of energy level was rather large (>10 meV), which made it difficult to examine small diamagnetic shifts with a sufficient accuracy less than 1 meV. Hence, for the quantitative evaluation of 2D confinement, it is important to prepare very narrow QWRs with good uniformity having the spectrum linewidth of less than 10 meV, and study their diamagnetic shifts in comparison with those of QWs.

In this work, we investigate PL properties of a series of T-shaped edge QWRs (T-QWRs) [8,9], whose cross sections are schematically shown in the inset of Fig. 1. We first show that their PL lines are always very sharp with linewidths of 4–7 meV, and then examine their diamagnetic shifts in magnetic fields up to 12 T, comparing them with those of reference QWs having the same thickness in the normal direction. The effect of lateral confinement on exciton wave functions in T-QWRs is quantitatively evaluated separately from the enhanced 2D excitonic effect caused by the confinement in the normal direction. In the smallest T-QWRs studied here, the compressed exciton

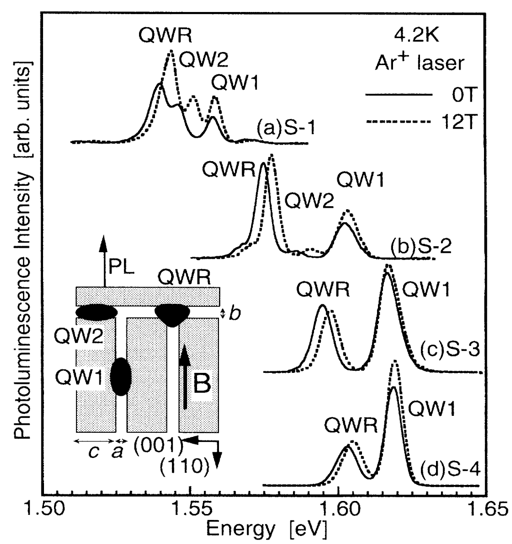


FIG. 1. Photoluminescence spectra measured at 4.2 K from the QWs (QW1 and QW2) and QWR region of four samples: (a) S-1, (b) S-2, (c) S-3, and (d) S-4. Solid lines are for zero magnetic field while dotted lines are for the field of 12 T. A basic structure of T-QWRs is shown in the inset, where QW1, QW2, and QWR are also defined.

 0031-9007/95/74(18)/3664(4)$06.00 

wave function is found to be smaller than that of any 2D excitons in GaAs QWs.

Four different T-QWRs (S-1–S-4) were fabricated by the modified molecular beam epitaxy (MBE) process called the cleaved-edge overgrowth (CEO) method which was reported by Pfeiffer *et al.* [10]. As shown in the inset of Fig. 1, multi-QWs were prepared in the first growth; they contain $n$ periods of GaAs QWs (QW1) of thickness $a$ separated by $Al_{0.3}Ga_{0.7}As$ barriers of thickness $c$. After the cleavage, a GaAs QW layer (QW2) of thickness $b$ and an $Al_{0.3}Ga_{0.7}As$ barrier were overgrown on the (110) cleaved surface to form the wire structures. Since QW1 is set close to, but always thinner than, QW2 ($a \leq b$) for all samples, QW1 has higher energy than QW2. Therefore the confinement of the QWR state is slightly stronger along the [110] (normal) direction than along the [001] (lateral) direction. The geometry parameters of each sample are as follows: $a = 10.0$ nm, $b = 12.5$ nm, $c = 200$ nm, and $n = 35$ for S-1; $a = 5.8$ nm, $b = 6.8$ nm, $c = 100$ nm, and $n = 50$ for S-2; $a = 5.1$ nm, $b = 5.6$ nm, $c = 31$ nm, and $n = 200$ for S-3; and $a = 5.1$ nm, $b = 5.1$ nm, $c = 31$ nm, and $n = 200$ for S-4 [11].

PL spectra of each sample were measured through an optical fiber with a 100 $\mu$m core diameter, which was attached to the (110) CEO surface of the sample in the geometry shown in the inset in Fig. 1. The sample was directly immersed in liquid helium, and placed in the bore of a superconducting magnet to apply a magnetic field up to 12 T perpendicularly to the (110) surface. The sample mounted on the fiber was then excited by an $Ar^+$ laser. PL from the sample was collected through the same fiber, and was dispersed into a 0.32 m grating monochromator.

The solid lines (a), (b), (c), and (d) in Fig. 1 are PL spectra of S-1, S-2, S-3, and S-4 measured at 0 T. For S-1 and S-2, three PL lines are clearly seen. Their origins are identified from the spatially resolved PL and cathodoluminescence [12], and are found to come from QWR, QW1, and QW2, respectively. In S-3 and S-4, no PL peak was observed from QW2, because the interwire separation $c$ (31 nm) is so small that most of the photogenerated carriers are efficiently collected by T-QWRs. Note that all the peaks are clearly observed with linewidths of 4–7 meV, indicating good uniformity of the structures. The energy spacing between the QWR and the QW2 peak corresponds to the energy difference of the 1D exciton in QWR and the 2D exciton in QW2. We will denote this quantity as the lateral confinement energy $E^*_{\mathrm{LC}}$ of excitons for T-QWR. From the PL spectra of Figs. 1(a) and 1(b), we have found that this energy is 6 meV for S-1 and 11 meV for S-2, respectively. Since the thickness of QW1 is equal to that of QW2 ($a = b$) in S-4, $E^*_{\mathrm{LC}}$ can be estimated from the energy difference of two PL peaks, QWR and QW1, in Fig. 1(d), which is 16 meV. Note that as the QWR size is reduced, $E^*_{\mathrm{LC}}$ is enhanced from 6, 11, up to 16 meV, which eventually exceeds the typical binding energy of 2D excitons in GaAs QWs [13–15].

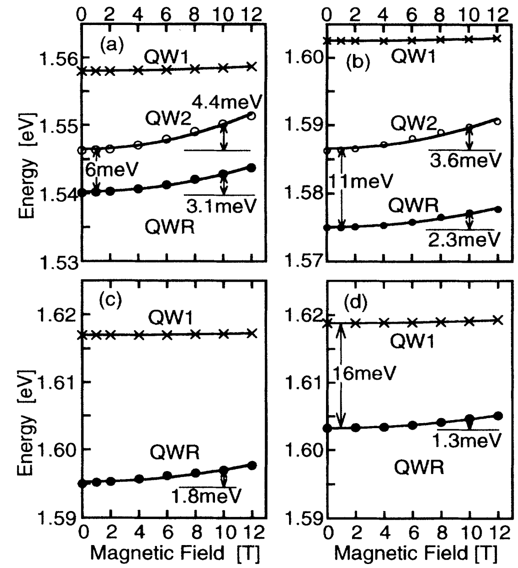


FIG. 2. Diamagnetic shifts of various PL peaks from S-1 (a), S-2 (b), S-3 (c), and S-4 (d). We also show diamagnetic shifts at 10 T, which are determined by fitting the data points with a parabolic relation. For the definitions of QW1, QW2, and QWR, see the text and the inset of Fig. 1.

When magnetic fields were applied, all the PL peaks shifted towards higher energy, as shown by dashed lines in Fig. 1. We plot in Fig. 2 the position of all the PL peaks as a function of magnetic fields $B$. Note that the amount of shifts is only a few to several meV even at 12 T. The use of higher magnetic fields enhances the shift but complicates the physical picture as will be discussed later. Hence the systematic and accurate evaluation of the diamagnetic shift can only be made on those QWR samples with PL linewidths comparable to or less than the shift. We believe that this condition was clearly met for the first time in this work.

When the Landau orbit is far larger than the exciton diameter, the effect of magnetic field $B$ is treated as a perturbation. In such a case, the diamagnetic shift of excitons can be expressed as $\Delta E = \beta B^2$ with diamagnetic coefficient $\beta$ being equal to $\langle e^2(x^2 + y^2)/8\mu \rangle$, where $\mu$ is the reduced mass of electrons and holes, and $\langle x^2 + y^2 \rangle$ is the effective area of excitons perpendicular to the magnetic field [16]. Therefore the value of $\beta$ represents the lateral size of excitons in the respective structure, which is expected to decrease as the lateral confinement is introduced.

Indeed, all the data are well fitted by parabolic relations in the low magnetic fields as shown by the solid lines in Fig. 2. The coefficient $\beta$ is found to be 31, 23, 18, and 13 $\mu$eV/$T^2$ for S-1, S-2, S-3, and S-4, respectively. At this point we wish to remark that this parabolic relation

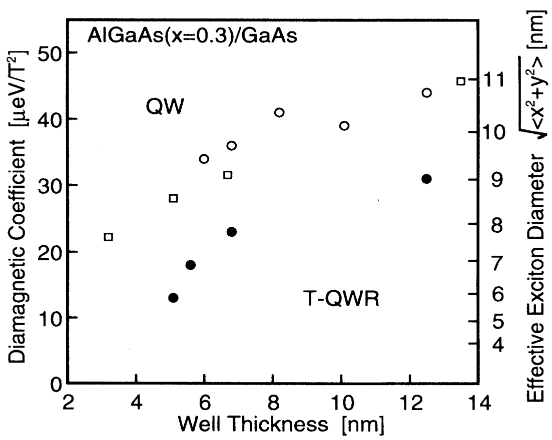


FIG. 3. The diamagnetic coefficient of four T-QWRs (solid circles) and nine $Al_{0.3}Ga_{0.7}As/GaAs$ QWs. The blank circles are for QWs grown on (110) substrate, while blank squares are for QWs on (001) substrate.

starts to break down at high fields, once the Landau orbit becomes comparable with or smaller than the exciton diameter. Hence the experimental determination of $\beta$ must be carefully made using the data in the region of relatively low field. In most of the previous work, this point was overlooked, which seems to have resulted in a relatively wide spread of data points [17].

In Fig. 3, we have plotted by solid circles the diamagnetic coefficient $\beta$ of four QWRs as a function of the well thickness $b$ of QW2. For comparison, we collected the coefficients $\beta$ of nine $GaAs/Al_{0.3}Ga_{0.7}As$ QWs having different well thicknesses $L_w$, and plotted them by blank circles and blank squares in Fig. 3. The blank circles are for QWs grown on (110) substrate, while blank squares are for QWs on (001) substrate. The data points of 12.5 nm thick QWs and 6.8 nm thick QWs are for QW2 of S-1 and S-2, respectively. For the quantitative discussion of the lateral confinement, we have defined the effective exciton diameter $d$ as $\sqrt{\langle x^2 + y^2 \rangle}$ and deduced $d$ from $\beta$ to introduce the scale of $d$ in Fig. 3. In this process, the bulk reduced mass $\mu = 0.058 m_0$ is assumed [18], because the reduced mass, or the exciton wave function, is usually dominated by the electron effective mass rather than the anisotropic hole mass, as suggested by the small difference of $\beta$ for (001) QWs and (110) QWs.

Now, we discuss data points in Fig. 3 to evaluate quantitatively the effect of lateral confinement in the QWRs. We should first point out in Fig. 3 that the diamagnetic coefficients $\beta$ of QWs get smaller, as the well thickness $L_w$ is reduced, and that the coefficients $\beta$ of four QWRs are all substantially smaller than those of corresponding QWs.

As for the QWs, the reduction of $\beta$, or the effective area of excitons, is caused by the enhanced Coulomb interaction between 2D electrons and holes, which is reflected also in the enhancement of exciton binding energy. As $L_w$ is reduced, and as the confinement in the normal direction becomes stronger, $\beta$ gets smaller from the bulk value to the 2D quantum limit value: for the bulk, $\beta_{3D} = e^2 a_B^2 / 4\mu = 109\ \mu eV/T^2$ and $d_{3D} = \sqrt{2} a_B = 16.9$ nm; for the 2D quantum limit, $\beta_{2D} = (3/16) e^2 a_B^2 / 4\mu = 20\ \mu eV/T^2$ and $d_{2D} = (\sqrt{3}/4) d_{3D} = 7.3$ nm. Here, we used the GaAs parameters of the effective Bohr radius $a_B$ of 12 nm and the reduced mass of $0.058 m_0$ [18].

This decrease of $\beta$ for 2D excitons in QWs indicates that the reduction of $\beta$ in QWRs below the level of its bulk value is caused partly by the confinement along the thickness direction and partly by lateral confinement. By comparing the values of $\beta$ or $d$ in T-QWRs with those of QWs with the same $L_w$, we can separate these contributions and evaluate the effect of lateral confinement separately from the confinement only along the normal direction which enhances 2D excitonic effect. For example, in S-1 where $a = 10.0$ nm and $b = 12.5$ nm, the effective exciton diameter $d$ is 10.7 nm for QWs, but it is slightly reduced to 9.0 nm in QWRs because of its lateral confinement. In S-2 where $a = 5.8$ nm and $b = 6.8$ nm, $d$ in QWs is reduced to 9.7 nm, whereas $d$ in QWRs is further squeezed to 7.7 nm. In sample S-4 where $a = b = 5.1$ nm, $d$ in QWs is 8.6 nm, but $d$ in QWRs becomes as small as 5.8 nm. These data clearly show that excitons are all laterally squeezed by the T-shaped potential profile in these QWR samples with feature sizes ranging from 5 to 12 nm. Note that the comparison of QWRs with QWs is quite precise for S-1 and S-2, since the array of T-QWRs and the reference QWs (QW2) were prepared simultaneously to give the identical thickness for QWRs and QWs.

We stress here that this systematic and accurate comparison of $\beta$ between QWRs and QWs is the only effective way to evaluate the effect of lateral confinement separately from the enhanced 2D excitonic effect. On the contrary, the comparison of $\beta$ in wires or dots with the bulk value ($109\ \mu eV/T^2$) does not provide any proof for the lateral confinement, although such is sometimes claimed [5]. In this sense, the present work provides the first reliable evidence of the lateral confinement of excitons in QWRs by means of diamagnetic shift measurements.

The next point to be noted in Fig. 3 is that $\beta$ of QWRs in S-1 is still larger than those of very thin QWs ($L_w < 5$ nm). In this QWR, the introduction of the T-shaped potential is effective in confining the 2D exciton laterally and reduces the effective diameter from 10.7 to 9.0 nm. However, the same level of squeezing is seen in 5 nm thick QWs where the enhanced 2D excitonic effect reduces the exciton diameter. This again shows that the simple reduction of $\beta$ or $d$ does not always provide proof for the lateral confinement.

The third point clarified by Fig. 3 is that the effective diameter of excitons in T-QWRs of S-4 goes below that of 2D quantum limit. Note in S-4 that $\beta$ is as small as $13\ \mu eV/T^2$ and $d$ is squeezed to 5.8 nm. We must compare these values with those of 2D excitons. In the limit of thin QWs (2D quantum limit), $\beta_{2D}$ is predicted to get as small as 20 $\mu$eV/T$^2$ and $d$ shrinks to 7.3 nm. In reality, as the thickness of the wave function in GaAs QWs remains finite, one expects that $\beta$ becomes saturated at around 22 $\mu$eV/T$^2$ and $d = 7.6$ nm, which is indeed demonstrated in 3 nm thick QW. Therefore we can conclude that the exciton wave function in the smallest T-QWR is squeezed more strongly than those of 2D excitons in GaAs QWs under the 2D quantum limit.

We wish to remark here the significance of the reduction in $\beta$, or the exciton diameter, in the context of optical device application. The optical transition probability of excitons is proportional to the squared amplitude $|\phi(0)|^2$ of the exciton wave function at the center position, which is the probability that an electron and a hole locate at the same position. Since $|\phi(0)|^2$ increases inversely proportional to the exciton effective area, and thus to the diamagnetic coefficient $\beta$, the observed reduction of $\beta$ in T-QWRs indicates the possibility of enhancing an optical transition process to a level that has never been achieved in any GaAs QWs.

In summary, PL spectra and their diamagnetic shifts have been studied in a series of high-quality T-QWRs whose linewidths are as small as 4–7 meV in careful comparison with reference QWs. It is demonstrated that diamagnetic coefficients $\beta$, which represent the lateral size of exciton wave function, are consistently smaller than those of 2D excitons with the same thickness, proving the effectiveness of lateral confinement in T-QWR structures. In T-QWRs formed by intersecting 5 nm thick QWs with the tight confinement energy of 16 meV, $\beta$ is found to get as small as 13 $\mu$eV/T$^2$, which is below the theoretical limit for 2D excitons in GaAs QWs. These results suggest that the optical transition probability of excitons in T-QWRs can be enhanced and exceed that of 2D excitons in any GaAs QWs.

One of the authors (T. S.) would like to thank JSPS for the partial financial support. This work is partly supported by a Grant-in-Aid from the Ministry of Education, Science, and Culture, Japan.

[1] D. A. B. Miller, D. S. Chemla, D. J. Eilenberger, P. W. Smith, A. C. Gossard, and W. T. Tsang, Appl. Phys. Lett. **41**, 679 (1982).
[2] H. Sakaki, Y. Arakawa, M. Nishioka, J. Yoshino, H. Okamoto, and N. Miura, Appl. Phys. Lett. **46**, 83 (1985).
[3] M. Kohl, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. Lett. **63**, 2124 (1989).
[4] A. S. Plaut, H. Lage, P. Grambow, D. Heitmann, K. von Klitzing, and K. Ploog, Phys. Rev. Lett. **67**, 1642 (1991).
[5] Y. Nagamune, Y. Arakawa, S. Tsukamoto, M. Nishioka, S. Sasaki, and N. Miura, Phys. Rev. Lett. **69**, 2963 (1992).
[6] H. Weman, E. D. Jones, C. R. McIntyre, M. S. Miller, P. M. Petroff, and J. L. Merz, Superlattices Microstruct. **13**, 5 (1993).
[7] R. Rinaldi, R. Cingolani, M. Lepore, M. Ferrara, M. Catalano, F. Rossi, L. Rota, E. Molinari, P. Lugli, U. Marti, D. Martin, F. Morier-Gemound, P. Ruterana, and F. K. Reihart, Phys. Rev. Lett. **73**, 2889 (1994).
[8] A. R. Goñi, L. N. Pfeiffer, K. West, A. Pinzuck, H. U. Baranger, and H. L. Stormer, Appl. Phys. Lett. **61**, 1956 (1992).
[9] W. Wegsheider, L. N. Pfeiffer, M. M. Dignam, K. West, S. L. McCall, and R. Hull, Phys. Rev. Lett. **71**, 4071 (1993).
[10] L. N. Pfeiffer, K. West, H. L. Stormer, J. P. Eisenstein, K. W. Baldwin, D. Gershoni, and J. Spector, Appl. Phys. Lett. **56**, 1697 (1990).
[11] The well thickness $a$ and $b$ are determined by comparing the PL data with calculated energy levels of QWs. Neglecting the additional enhancement in the binding energy of 2D excitons, we used the following parameters: the electron mass $0.067m_0$, the hole mass $0.45m_0$ ($m_0$ is the free electron mass), GaAs band gap 1.519 eV, and conduction (valence) band offset 0.243 (0.131) eV [18]. The expected error of this estimation process for well thickness is empirically within about one monolayer.
[12] T. Someya, H. Akiyama, and H. Sakaki (unpublished).
[13] R. C. Miller, D. A. Kleinman, W. T. Tsang, and A. C. Gossard, Phys. Rev. B **24**, 1134 (1981).
[14] J. C. Maan, G. Belle, A. Fasolino, M. Altarelli, and K. Ploog, Phys. Rev B **30**, 2253 (1984).
[15] S. Tarucha, H. Okamoto, Y. Iwasa, and N. Miura, Solid State Commun. **52**, 815 (1984).
[16] O. Akimoto and H. Hasegawa, J. Phys. Soc. Jpn. **22**, 181 (1967).
[17] G. E. W. Bauer and T. Ando, Phys. Rev. B **37**, 3130 (1988), and references therein.
[18] *Physics of Group IV Elements and III-V Compounds,* edited by O. Madelung, M. Schulz, and H. Weiss, Landort-Börnstein Numerical Data and Relationships, New Series, Group III, Vol. 17a (Springer, Berlin, 1982).