10 nm-scale edge- and step-quantum wires and related structures: Progress in their design, epitaxial synthesis and physics


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Abstract

This paper describes our recent studies to design and epitaxially synthesize 10 nm-scale quantum wire (QWR) structures and to clarify their transport and optical properties. We discuss first the epitaxial growth and physics study of both field-induced edge QWRs as well as T-shaped edge QWRs. We, then, propose two new edge QWR structures in which electric fields play greater roles in the carrier confinement. We then summarize our recent work on step QWRs, in which periodic bunched steps on a (111) B GaAs plane modulate the motion of 2D electrons at n-AlGaAs/GaAs heterojunctions. Finally, we discuss several approaches by which 10 nm-scale QDs are formed by the extended use of epitaxial techniques originally developed for the fabrication of QWRs. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Electrons confined in quantum wires (QWRs), quantum boxes/dots (QBs/QDs) and related structures have attracted much attention because of their importance both in physics of low-dimensional systems and in advanced electronics. For example, planar arrays (superlattices) of coupled QWRs and/or QB/QDs proposed in 1976 by one of us [1] are found to have unique transport properties, such as negative transconductances [2], negative differential conductances, and commensurate magnetoresistance (Weiss) oscillation [3,38]. Also, the double barrier transport through zero-dimensional (0D) states in a quantum dot is found to exhibit unique properties originating from the charging effect and the discreteness of its atom-like level structure [4]. The transport of one-dimensional (1D) electrons through QWRs is also shown by theory and experiment to have features resulting from the finiteness of their transverse modes [5,6] and the enhancement of electron–electron interaction [7].

Photonic properties of 1D and 0D electrons and holes have also attracted wide attention, as they reflect their peaked density of states and the enhanced
Fig. 1. Examples of epitaxially grown quantum wire (QWR) structures (a)–(e) and self-organized quantum dots (f). See the text for detailed accounts of ridge QWR (a), groove QWR (b), field-induced edge QWR (c), T-shaped edge QWR (d), and one example of step-induced QWRs (e).

excitonic interaction. It is predicted that the use of such systems for lasers and modulators would provide desirable performances not achievable in 3D and 2D systems [8–10].

Although various features of 1D/0D systems were demonstrated, most of these experiments were conducted at low temperatures on samples with sizes in the range of 50–200 nm. The formation of 10 nm-scale QWRs and QB to QDs is, however, strongly desired, as it critically enhances both the energy-level spacing and excitonic interactions, and results in quantum-limit conditions (even at room temperature) which are indispensable for most device applications as well as for the physics study of one- or a few-level electron systems.

Despite the early pessimism, the material technology to synthesize or to form such 10 nm-scale QWRs and QBs has made impressive progress over the last 10 years and has provided several approaches, as shown in Fig. 1. In this article, we discuss some advances in this area. Specifically, we describe in Sections 2 and 3 our recent work on edge QWR- and step QWR-structures. In Section 4, we briefly examine novel epitaxial methods to prepare QD structures in comparison with the self-assembly scheme.

2. Recent advances in edge quantum wire (E-QWR) structures

2.1. Field-induced edge quantum wires (F-EQWRs)

It was pointed out in 1980 [5] that a 10 nm-scale QWR can be formed in the edge region of undoped quantum wells (QWs) with the well width $L_z$ of about 10 nm, if electrons are confined by the QW potential $V(z)$ along the $z$-axis and by an electric field $F(y)$ along the $y$-axis which pulls electrons towards the edge plane. Such a space-charge field $F(y)$ can be generated by forming a positively biased gate electrode or a positively charged n-type barrier layer onto the edge of QWs, as shown in Fig. 1c. Indeed, this type of field-induced edge QWRs have been successfully fabricated by overgrowing an n-AlGaAs layer on either the cleaved edge [11,12] or the facet plane [13] of a GaAs/AlGaAs QW structure. Quantized conductance steps have been clearly observed for such an edge QWR for the wire width $L_z$ as small as 14 nm [12].

When the width $L_z$ of pre-grown QWs is of the order of 70–100 nm, the spacings of 1D subbands decrease to a few to several meV, leading to the formation of quasi-1D electron gas that occupies several subbands [13]. From the magnetic depopulation analysis of Shubnikov de Haas data, such subband structures have been clarified. It has been recently noted that this subband structure can be drastically modified if dopants are introduced into the pre-grown GaAs/AlGaAs multi-QW structure in such a way that a sheet of donors sit in the center of each AlGaAs barrier layer, while a sheet of acceptors lies in the center of each GaAs QW layer [14]. For this doping scheme, quasi-1D electrons formed in the edge region of GaAs QWs are further driven towards two corner regions of each QW because of additional electric fields induced by the dopants. This modified field-induced E-QWR approach results, therefore, in the formation of novel 1D electron gas, which is confined rather tightly in the two corners of each QW. Of course, for such structures, one must set the areal densities $N_D$ and $N_A$.
of these donors and acceptors to be equal and high (\(>10^{12} \text{ m}^{-2}\)) [14].

2.2. T-shaped edge quantum wires (T-EQWRs/T-QWRs)

It was pointed out by Chang et al. [15] that both electrons and holes can be confined in another type of edge QWRs, where a second quantum well layer (QW-2) is deposited onto the edge plane of a pre-grown (undoped) quantum well structure (QW-1), as shown in Fig. 1d. This is because the QW confinement energy \(E_{c}(2D)\) of 2D electrons, which is proportional to the inverse of the squared effective well width \(L_{z}^{2}\), decreases locally in the intersection region of QW-1 and QW-2, making it energetically favorable for electrons to reside in a laterally confined one-dimensional electronic state \(E_{c}(1D)\). The strength of confinement in this T-shaped QWR is determined by the energy difference \(\{E_{c}(2D) - E_{c}(1D)\}\), which we call, hereafter, the lateral confinement energy. One expects that this energy increases when the well widths, \(d_1\) and \(d_2\), of QW-1 and QW-2 are both substantially reduced (\(<7\) nm). The same argument applies to holes, except that the lateral confinement energy \(E_{h}(2D) - E_{h}(1D)\) of holes is normally far smaller by a factor of 3–5 than that of electrons because of their heavier effective mass.

When both an electron and a hole are simultaneously introduced in a T-QWR, they attract each other and form an exciton. It is theoretically predicted that the binding energy \(E_{B}(1D)\) of such 1D excitons is substantially enhanced over that \(E_{B}(2D)\) of 2D excitons, when the cross-sectional sized \(d^*\) or diameter of excitons is reduced well below 10 nm. One interesting issue is how much the binding energy \(E_{B}(1D)\) is enhanced in real T-shaped QWR. One should also clarify how this excitonic state influences performances of QWR lasers and other photonic devices.

The fabrication of T-shaped edge QWRs was first achieved by Pfeiffer and his coworkers by the use of cleaved edge overgrowth (CEO), mentioned earlier, and followed by a series of works of both his and our groups [11,16–20]. For example, Wegscheider et al. observed lasing at the wavelength close to the excitonic luminescence and suggested the possibility of excitonic lasing [17]. Here, we describe our recent study to estimate the spatial spread and the binding energy \(E_{B}(1D)\) of 1D exciton state [18–20].

For this purpose, we prepared a series of GaAs/AlGaAs T-QWR samples, where a QW-2 layer of various thickness \(d_2\) is overgrown onto the edge of QW-1 layer of fixed thickness \(d_1\). Photoluminescence (PL) spectra measured at 4.2 K showed three peaks which were ascribed by the spatially resolved study to the T-shaped QWR and two neighboring wells, respectively. The energy positions of these peaks are plotted in Fig. 2 as functions of the (effective) thickness \(d_2\) of QW-2. Note that, as \(d_2\) increases, the peak from QW-2 lowers its energy, whereas that from QW-1 keeps its position. In contrast, the energy \(E_{PL}(1D)\) of the PL peak from the T-QWR is found to be always lower than those \(E_{PL}(2D)\) of neighboring QWs by some amount. This energy spacing \(E_{PL}(2D-1D)\) gets maximum (about 18 meV) for a balanced T-QWR, where PL peak energies from QW-1 and QW-2 coincide. As this balance weakens, the PL peak from the T-QWR approaches the lower branch of PL peaks from QWs, indicating that the QWR state tends to spread more in one of two QWs having a thicker well width.

This spacing \(E_{PL}(2D-1D)\) of PL peaks comes from three components. The largest among them is the lateral confinement energy of electrons, that is the energy difference \(E_{c}(2D-1D)\) between the ground-state energy \(E_{c}(2D)\) of 2D electron in the neighboring QW and that \(E_{c}(1D)\) of 1D electron in the T-QWR. Then comes the difference \(E_{h}(2D-1D)\) of the ground-state energies of 2D and 1D holes in the system, which is known to be far smaller than that \(E_{c}(2D-1D)\) of electrons because of their heavier effective mass. The third component is the difference \(E_{B}(1D-2D)\) of the binding energy \(E_{B}(1D)\) of 1D excitons in QWR and that \(E_{B}(2D)\) of 2D excitons in neighboring QWs.

By comparing the measured spacing \(E_{PL}(2D-1D)\) of PL peaks with the calculated spacing of one-particle ground-level energies of electrons and holes, we can evaluate the enhancement of the exciton binding energy in 5 nm-scale T-shaped AlGaAs/GaAs QWR over that of 5 nm-thick AlGaAs QW and conclude it to be 3–5 meV. Hence, the binding energy of this 1D exciton is estimated to be 16–18 meV, which is in a reasonable agreement with the recent theoretical results [21,22,39]. By conducting a similar measurement on a series of 5 nm-scale T-shaped QWR sample with AlAs
Fig. 2. The energies of three photoluminescence (PL) peaks coming from a series of T-shaped GaAs/AlGaAs edge QWR structures; they are prepared by growing the second QW layer (QW-2) of various well widths onto the cleaved edge of a common wafer containing an identical QW (QW-1). The lowest peak is from the T-QWR, whereas the upper two are from QW-1 and QW-2, respectively (Someya et al.).

barriers, we have found out that the spacing $E_{PL}(2D-1D)$ of PL peaks of the QWs and the T-QWR gets as large as 30 meV [19]. Again by comparing it with the energy difference in the calculated ground levels of 2D and 1D electrons, the binding energy of 1D excitons in 5 nm-scale GaAs/AlAs QWR is estimated to exceed 25 meV. This value is substantially larger than that predicted [21,22,39]. The origin of this discrepancy is not fully understood but may be linked with the monolayer roughness at the hetero-interface, since the line widths of PL peaks are all in excess of 10 meV, which suggests that both 2D and 1D excitons can be influenced by the roughness-related localization as well as the uncertainty of local well widths [23].

2.3. Edge quantum wires induced by converging electric fields

Recently, we proposed a novel double-barrier resonant tunneling diode structure shown in the inset of Fig. 3[24]; here an AlGaAs/GaAs QW layer (QW-2) and n-GaAs 3D electrode layers are consecutively grown onto the edge plane of a pre-grown epi-layer, where an n-type QW electrode (QW-1) is embedded. If a positive voltage is applied to the 2D electrode with respect to the 3D electrode, a converging electric field develops, which drives electrons from the broad 3D electrode to the very thin 2D electrode via QW-2 layer inbetween. By solving the Schrödinger equation, we have shown that a 1D bound state is formed inside of QW-2 because of the lateral confinement action of the converging field. If the bias of opposite polarity is applied, electrons from the 2D electrode are injected into the QW-2 layer and undergo a diverging field. Transport properties of such a 3D-2D resonant tunneling diode is shown in Fig. 3, where negative
differential resistance is seen. A peak on the positive bias side is likely to be borne by the QWR state mentioned above.

3. Recent advances in step-quantum wire structures

The use of atomic steps on vicinal substrates to introduce 10 nm-scale periodic potentials into 2D electron systems has been tried in various schemes but has met so far with only limited success [25–27,40,41]. It is because the resulting potential modulation is often too weak or too random to induce well-defined QWR states or planar superlattice (P-SL) states. Note, for example, periodic mono-atomic steps seen on a tilted (100) GaAs plane give rise to the surface corrugation of about 0.3 nm in height, which induces only a weak potential modulation (less than 10 meV), unless the electron is confined in a thin QW of 5 nm or less. To strengthen the potential modulation, a half-mono-layer GaAs and another half-mono-layer of AlAs are alternately deposited to form in-plane (tilted) superlattice structures. However, the randomness of steps and the partial mixing of GaAs and AlAs have weakened the potential modulation far below the desirable level [25–27,40,41].

As an alternative approach, several groups have recently explored the possibility of using spontaneously organized bunched step structures, where a quasi-periodic surface corrugation is formed with the height of 1–5 nm [28–30,42]. Here we describe our recent work along that line to show that P-SLs of reasonable quality can be formed by depositing an n-AlGaAs barrier layer on a freshly grown undoped GaAs layer on a vicinal (111) B surface, where multi-atomic steps of about 18–20 nm in periodicity can be formed with small inhomogeneities, as shown in Fig. 4. Although the morphology of these surface steps depends sensitively on the growth condition, it has been found that the use of high arsenic pressure is effective in reducing the randomness of steps and leads to the quasi-periodic step structure for the tilt angle of 2–8.5° from the (111) plane. The step structure shown in Fig. 4 is obtained for the tilt angle of 8°, which means that the height of bunched step is around 2 nm.

Transport properties of 2D electrons in selectively doped n-AlGaAs/GaAs heterojunctions on vicinal (111) B planes with the tilt angles of 5° and 8° have been studied. Electron mobilities normal to and parallel with the steps were measured at 4.2 K as functions of the electron concentration Ns, as shown in Fig. 5. Note that the mobility along the steps increases monotonically with Ns, reaching as high as 300 000 cm²/V s. This tendency is similar to the mobility behavior of high-quality 2DEG, which suggests that the roughness along the steps is almost negligible and the rise of Fermi energy, i.e. the increases of Ns, has led to the enhancement of mobility.

In contrast, the mobility normal to the steps has shown a similar behavior only in the region of low Ns, and it saturates at Ns = 3 × 10¹¹/cm² and then falls markedly, as Ns is further raised. In the limit of highest Ns, the mobility across the steps is almost 10 times lower than that along the steps. This unique behavior of mobilities indicates that the scattering of electrons by the step structure gets more effective at high Ns, where the Fermi wavelength of electrons becomes close to the (twice of) step periodicity. This agrees qualitatively with the theoretical prediction that the back scattering rate by interface steps should
increase and the mobility should drop, when more electrons start to satisfy the momentum conservation in the step-induced back scattering event. To examine the validity of this interpretation, one must consider the role of gate electric fields, since the strength of the electron interaction with interface steps depends generally on the gate voltage; indeed, in the case of Si MOSFETs, the scattering rate by interface roughness is known to rise, when the wave function of 2D electrons is pulled more strongly towards the interface by increasing the gate electric field (and $N_s$). In any case, the strong anisotropy of mobility and its unique dependence on $N_s$ observed in Fig. 5 show clearly that quasi-periodic bunched steps at the interface give rise to a unique feature of the electron transport phenomena in this system.

4. Future tasks on quantum wires and crossover with quantum dots

4.1. Future tasks on epitaxially grown QWRs

As mentioned above, epitaxial technology to prepare 10 nm-scale quantum wire structures has made remarkable progress over the last 10 years. In particular, the CEO method has been used to prepare edge QWRs, with which unique features of 1D electrons and excitons have been demonstrated. However, edge QWRs formed on a cleaved edge have one weakness in that it is quite difficult to perform subsequent processings needed for the device fabrication. One way to solve this problem is to prepare edge QWRs with no use of the cleavage process. In fact, one can first deposit GaAs selectively on a mesa pattern and form a facet structure consisting of a top (100) plane and two (111)B side planes; the subsequent deposition of a AlGaAs/GaAs quantum well on such a facet results in a novel QW of a finite length with its two (111)B side planes being exposed at the edge of the QW. Indeed, a number of field-induced edge QWRs have been formed by growing n-AlGaAs layer onto the (111)B edge plane of such facet structures and their transport properties have exhibited 1D nature of electrons for the wire width down to 50 nm [13]. In forming such QWRs, a facet corner defined by the top (100) plane and the side (111)B plane has to be made as sharp as possible, since any rounding of the corner spoils the cross-sectional shape of the wire. In addition, the flatness of the side (111)B plane is also crucial, as any roughness on this plane results in the scattering of 1D electron gas.

As briefly mentioned in the introduction section, ridge- and groove-QWR approach allows the formation of 10 nm-scale wires along the ridges or the grooves in selectively grown sharp facet structures which are formed on mesa patterns engraved into a substrate with conventional lithography. Though not much discussed in this article, their importance will further grow, as their shape controllability has been substantially improved. Indeed, 1D nature of electrons in these wires has been revealed not only by optical studies but also by some recent transport studies [31]. One of the remaining tasks on these QWRs is the further refinement of growth processes, as the reduction of non-radiative centers is desired.
especially for photonic applications. Another challenge on ridge/groove wire approach is to extend this method for the formation of quantum dot structures. This will be addressed in the next subsection [32,33].

As described in Section 3, the use of single or bunched atomic step structures on vicinal substrates for the formation of quantum wire arrays is quite attractive for several reasons. Firstly, this step-wire approach allows the formation of dense wire arrays with no burden or cost of lithography. Also, this method allows the formation of wire arrays in almost planar forms, which makes it easy to perform the subsequent processing steps. Hence, this is an approach that is most compatible with conventional device technology. Hence, it is worthwhile to investigate further the formation mechanisms of such step structures so as to minimize both the meandering of wires as well as the randomness of wire periodicities. One must also explore ways to better control the profile of an in-plane potential $V(x, y)$ induced by these steps.

4.2. Crossover and extensions to quantum dot systems

For a long time, the fabrication of 10 nm-scale quantum dots (QDs) and quantum boxes (QBs) was considered to be far more difficult than that of quantum wires. However, this view has been recently modified with the advent of two novel approaches, namely (a) self-assembled quantum dot formation by the Stranksi–Krastanov growth mode and (b) the extended use of quantum wire formation processes to fabricate QD/QB structures. Here, we briefly discuss recent progress in self-organized dots and new attempts to extend epitaxial methods to form 10 nm-scale QD structures.

The self-organized growth of strained InAs or InGaAs QDs on lattice mismatched GaAs has been a subject of intense studies. Although the position control of these dots is still hard, each dot fully confines electrons and provides discrete electronic states with the energy-level spacing $(E_2 - E_1)$ of typically 50 meV. This system is already attractive for photonic device applications. Indeed, QDs lasers have been fabricated with these dots and some of them have demonstrated the predicted reduction of temperature sensitivity of threshold current, indicative of the discreteness of electron and hole states. The threshold current $J_{th}$ of QD lasers has been reduced to a level comparable to that of QW lasers. To lower $J_{th}$ further, one needs to refine the growth procedure so as to reduce the inhomogeneous broadening of the energy levels well below the thermal energy $k_B T$. Hence, further studies on growth mechanisms of QDs are strongly desired to exploit the full potential of QD lasers and other photonic devices [34].

Recently, a number of groups have explored the possibility of using self-assembled QDs for memory devices. In some attempts, InAs (or Si) QDs are embedded between the gate and the channel of GaAs/AlGaAs (or Si MOS) FETs [35,36,43]. By applying an appropriate voltage to the gate, one can induce the tunneling (or thermonic) current from the channel towards the dots and fill up each QD with one or few electrons. This trapped charge shifts the FET threshold voltage $V_{th}$, which can be detected (read) by measuring the conductance of the FET. Although the retention time of this stored charge depends on the specific structures of FETs and needs to be better controlled, this type of QD-embedded FETs possess potentials as a unique non-volatile memory device. In addition, the use of closely spaced nano-scale Si islands has been explored to make a multi-barrier single-electron tunneling device and its memory action has been demonstrated at room temperature [37].

In addition to the Stranski–Krastanov growth of QDs, some other epitaxial methods have been recently explored for the fabrication of 10 nm-scale QDs. Here we discuss some of them and point out that most of them are based on the extension of epitaxial techniques originally developed for the QWR formation. As described earlier, at least three approaches have been developed to form 10 nm-scale QWRs. In the edge quantum wire (E-QWR) approach, a (1 0 0) QW plane intersects with a (0 1 1) cleavage plane or a (1 1 1) B facet plane to define an edge QWR running along the [0 1 − 1] direction. In the ridge/groove QWR approach, a QWR parallel to the [0 1 − 1] axis is defined as the intersection of two (1 1 1) B facet planes formed by the selective growth. In the step QWR (S-QWR) approach, QWRs are formed along atomic steps on vicinal substrates, which run along the [0 1 1] or [0 1 − 1] axis on the (1 0 0) plane or parallel to the [2 − 1 − 1] or [0 1 1] axis on the (1 1 1) B plane. Below we discuss how the epitaxial techniques
originally developed for the QWR growth can be extended further to form QDs.

It has been pointed out by Wegscheider and Pfeiffer [32] that 10 nm-scale QDs can be formed, if an epitaxial wafer containing T-shaped edge-QWRs is first cleaved to expose the cross section of QWRs and then a third QW layer is overgrown onto it. Indeed this structure has been realized by Wegscheider et al. and an extremely narrow luminescence line indicative of a 0D exciton state has been observed [32]. A somewhat related approach was independently proposed by one of the authors (H.S.), in which cross section of step QWRs is first exposed and another QW layer is overgrown onto it to form 10 nm-scale QD structures [33]. Similarly, one can also form a QD by the overgrowth of a QW layer onto the exposed edge of a ridge or groove-QWR structure.

Clearly, these three approaches mentioned above make use of one of epitaxial QWR approaches (E-, S-, and R/G-QWR) first, which is followed by the edge-overgrowth (E) process. Hence, they can be termed as edge–edge (EE) approach, step–edge (SE) approach, ridge/groove–edge (RE/GE) approach, respectively. Naturally, one can further exploit some other combinations of these techniques. For example, the combined or simultaneous use of step QWR- and ridge/groove QWR-techniques (to be referred as SR/SG), and the double use of step QWR technique (SS) and ridge/groove QWR technique (RR/GG) would be all effective. Indeed, some of them have been already tested by a few experiments, elucidating potentials of these approaches. Note that these methods of QD formation based on the combined use of QWR growth techniques will play important roles in the future research of quantum dot systems.

References

[29] See for steps on (1 1 1) planes, Y. Nakamasa, S. Koshiha, H. Sakaki, J. Crystal Growth 175 (1997) 1092.