V-shaped AlGaAs-GaAs Quantum Wires Grown by Flow Rate Modulation Epitaxy

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Abstract

Self-limiting effects in flow rate modulation epitaxy (FME) have proven very effective in suppressing size fluctuation of AlGaAs/GaAs quantum wires (QWRs) because growth thickness is determined solely by the number of flow cycles of source materials. In addition, by using tertiarybutylarsine (TBA), as well as better alignment of the V-grooves along the crystal directions and additional chemical etching, true one dimensional excitonic states are extended more than a few microns. These uniform AlGaAs/GaAs QWRs were employed for FETs. Conductance quantization was observed at a relatively high temperature of 37K.

1. Introduction

Selective growth on a V grooved GaAs substrate has been one of the most popular methods of realizing a nano-scale crescent shaped quantum wire (QWR) beyond the lithographic resolution¹. However, the QWR has been nothing but an array of quantum dots (QBs) lined up randomly along the V-groove direction. Because even a mono-atomic layer indentation of 0.28nm at the hetero-interface or random distribution of impurities causes an energy difference of several meV², and isolates the excitonic states along the QWR at cryogenic temperature. Excitons in the QWR had been either diffusive³ or dot-like², corresponding to whether the period of the irregularity is shorter or longer than excitonic Bohr radius of the order of 10 nm. Therefore, it remains a real challenge to realize the size controllability at an atomic scale and to bring to fruition a number of promised effects in quantum nanostructures such as enhanced electron mobility, optical gain, and nonlinear susceptibility.

We discovered a new self-limiting growth of crescent shaped QWRs on V-grooved substrates by a flow rate modulation epitaxy (FME)⁵,⁶. This is a modified metalorganic vapor phase epitaxy (MOVPE), in which 3- and 5-group elements are supplied alternatively. In this technique, QBs with the length of 10 - 100nm were well separated along the V-groove and fine PL spectra were isolated by far-field optics for the first time². They have also brought to light the singular characteristics of one dimensional excitons such as quantum-size effects on radiative lifetimes⁷, the importance of the exchange interaction as verified by the polarization dependence of the exciton
energy splitting and the formation of bi-excitons upon high intensity excitation.

In addition to the careful alignment of the V-grooves along the crystal directions and additional chemical etching, the use of less toxic tertiarybutylarsine(TBA) has proven to be effective in the suppression of step bunching and improving the uniformity of AlGaAs/GaAs quantum wires (QWRs). The lifetime of excitons in the QWR prepared with TBA was much longer than that with arsine, which indicates that the non-radiative recombination center is also suppressed by TBA. Spatially resolved measurements using scanning micro-photoluminescence have verified that uniformity of the QWRs has reached macroscopic length of a few microns.

These uniform QWRs were applied for both one dimensional (1D) lasers and FETs. The QWR lasers achieved fundamental sub-band lasing for the first time. Well-defined conductance steps are observed in a GaAs QWRFET even at 35K, which indicates the ballistic transport of electrons in a 1D electron channel. The onset of negative resistance also indicates the suppression of electron scattering in a 1D channel.

In this presentation, improvement of the atomic scale uniformity in the present stage of QWRs is demonstrated in contrast with the older generation, together with the optical properties of true 1D excitons and 1D electron transport in the QWR FETs.

2. Flow rate modulation epitaxy (FME) with arsine and TBA

The epitaxial growth was carried out using a low-pressure (76 Torr) horizontal MOVPE reactor on 2-4 μm pitch V-grooved GaAs substrates, using TMAl and TEGa as the group 3, and arsine or TBAs as the group 5 sources, respectively. The sample structure typically consisted of a GaAs buffer layer, an Al0.4Ga0.6As barrier layer, one or multiple FME-grown GaAs wire layers, an Al0.4Ga0.6As barrier layer, and a GaAs cap layer.

The difference of the growth rate of GaAs on (001) and (111) surface produces a crescent shaped quantum wire structure. The growth temperature was 630 - 660°C. The gas supply sequence used for FME growth was shown in Fig.1. Arsine (or TBA) and TEGa were supplied in turn with the duration and interval of 1sec each in the FME period. The amount of AsH3 (or TBA) supplied in one flow period was fixed at about 2.98 μmol (17.8 μmol for TBA). A small amount of AsH3 (1-2 μmol/min) or TBA (12 μmol/min) was supplied throughout the growth to prevent the evaporation of arsenic species and impurity incorporation during Ga flow and H2 purge periods. Figure 2 shows the growth rate of QWRs at the V-groove against the flow rate of TEGa and that of the quantum wells (QWs) at the flat region in case of TBA (left) and AsH3 (right), respectively. The growth rate per FME cycle is expressed in the unit of monolayer thickness of 2.83 Å along the (001) facet. The growth rate of the quantum wire region (solid circle) increased step-like, while that of planar surface increased linearly against the flow rate of TEGa. Self-limiting effects is evident in the FME growth of GaAs both in AsH3 and TBA for 5-group element. Therefore, we can count the number of atoms in order to assign the size of the quantum nanostructure. As shown in Fig.3, gallium atoms saturated at the bottom of the V groove have enough time to migrate to the unsaturated flat region leaving the mono-atomic layer of gallium.
during each period. The enhanced surface migration of Ga along the (111)A surface during the arsenic lean conditions realized a narrow crescent quantum wire with a nominal width of 30nm and a thickness of 3 – 15 nm at relatively low growth temperatures, which are effective to reduce the carbon incorporation. Figure 4 shows the TEM image of a vertically stacked 4-QWR sample using TBA. As can be seen in this figure, crescent-shaped QWRs were successfully formed at the V-groove bottom. Further, the two side-wall facets with an intersecting angle of about

Fig.4 Cross sectional TEM image of GaAs/AlGaAs crescent shaped QWR prepared by TBA.

78° are closer to the exact (111)A facet (intersecting angle: 72°) than structures grown using AsH₃ (intersecting angle: 82°). The steeper intersecting angle causes a larger subband spacing of 58meV in TBA than that of 46meV with AsH₃ at the nominal thickness of 4.5nm.

Fig.3 Principle of the FME growth. Saturated Ga atoms at the valley regions move toward unsaturated flat regions, leaving the atomically flat surface during each period.
Figure 5 shows temperature dependent PL decay times of the ground state peaks of the TBA and the AsH₃ samples, respectively. The decay time of the TBA sample increased continuously with increasing temperatures as high as 240 K, at which point it began to decrease. The AsH₃ sample began to decrease at 150 K. It is theoretically predicted that the radiative lifetime of a QWR should increase continuously in proportion to the square root of the temperature. However, the nonradiative recombination process, which will become faster as the temperature increases, competes with the radiative recombination process and results in a maximum. A higher temperature of the maximum decay time means a lower density of nonradiative recombination centers. Therefore, it was confirmed that the nonradiative recombination centers grown by TBAs were reduced compared to those grown by AsH₃.

3.Optical properties of excitons in the QWRs

Uniformity of the QWRs was estimated by the scanning microscope spectra in which microscope objective lens was translated with a piezo-electric actuator along the V-groove. Figure 6 contrasts scanning microscope images (upper row) and PL spectra (lower row) of the last generation (left column) and new generation (right column) of QWRs, respectively. The vertical axis of the scanning microscope image corresponds to the position along the QWR. In the last generation QWR, which was prepared using the FME method by AsH₃ without additional etching of the substrate, several spiky peaks are observed in the PL spectra as is seen in the left lower quadrant. They are observed as a number of short stripes in the scanning microscope images, because QWRs are separated into pieces within the observation area of about 1 µm. In contrast, in the new generation QWR, which was prepared by TBA and with additional etching, only one peak is found at the PL spectra and is extended for 2-3 µm in the scanning microscope image (lower right quadrant). The half width of the PL spectra is rather broad (>300 µeV) compared with the last generation (<50 µeV). Thermalization was predominant in the new sample because quantization energy along the QWRs was reduced to the order of 10 µeV with a coherent length of a few microns. In the last generation QWRs, with the nominal length of 20-100nm, excitons were completely localized along the V groove with the quantum energy of a few meV, resulting in the very sharp luminescent spectra.

4.Conductance steps in GaAs QWRFETs

It is easy for the present lithography to realize an intrinsic part of the semiconductor device within a few microns comparable to the coherent length of our QWR. Therefore, there is a great chance to realize a ballistic transistor where electron flow is controlled without scattering. Figure 7 shows a top view and a schematic cross section of the 1 µm gate GaAs QWRFET. We employed a 10nm thick GaAs QWR with the nominal subband spacing of 20meV, and sandwiched it with undoped Al₀.₃₆GaAs spacers (10nm) and Si-doped Al₀.₃₆GaAs modulation doped layers (50nm). Figure 8 shows static drain voltage versus drain current characteristics at 35K.
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<thead>
<tr>
<th>Last generation of V-groove wires</th>
<th>New generation of V-groove wires</th>
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<tbody>
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<td>Scanning Image</td>
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<td>• Small localization sites (20 to 200 nm)</td>
<td>• Extended emitting sites (0.5 to 2 µm)</td>
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<td>• Sharp peaks (&lt; 50 µeV)</td>
<td>• Wider peaks (&gt; 300 µeV)</td>
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Fig.6 Scanning microscope images and micor PL spectra of last generation and new generation of QWRs.

Fig.7 Top view and schematic cross section of the 1 µm gate GaAs QWRFET

![Top view and schematic cross section of the 1 µm gate GaAs QWRFET]

Fig.8 Static drain voltage versus drain current characteristics at 35K.

![Static drain voltage versus drain current characteristics at 35K](VDS=0.6 V)

Fig.9 Gate voltage versus drain current characteristics at 35K.

![Gate voltage versus drain current characteristics at 35K](VDS=0.6 V)
I-V curves increase nonlinearly against gate voltage at low drain voltage. Negative differential resistance shows up at drain voltage higher than 0.4V. In Fig.9, there are clear steps in drain current against gate bias. Current steps at drain bias higher than 0.1V indicate the contribution of the higher subband.

5. Conclusion

Steady progress has been made to improve the uniformity of the QWRs on a V grooved GaAs substrate. In the FEM technique, the growth thickness is determined solely by the number of flow cycles of source materials, due to the enhanced surface migration of the 3-group element to the unsaturated planar region. TBA, as well as the better alignment of the V-grooves along the crystal directions and additional chemical etching, are also effective to suppress step bunching and impurity incorporation.

The true 1D nature of excitons gradually manifests itself as the coherent length of the QWR reaches the macroscopic dimension of a few microns.

These uniform AlGaAs/GaAs QWRs are applied to 1D FETs. Clear conductance quantization is observed in the QWR FETs at a relatively high temperature of 35K.

References