Flow rate modulation epitaxy of AlGaAs/GaAs quantum wires on nonplanar substrate

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Flow rate modulation epitaxy (FME) is applied to the low-temperature growth of AlGaAs/GaAs quantum wires (QWRs) on nonplanar substrates. The growth selectivity is found to be enhanced greatly by the use of FME, as compared with the conventional metalorganic chemical vapor deposition due to the enhanced migration of Ga species. An AlGaAs/GaAs QWR with a central thickness of about 9 nm and a lateral width of about 28 nm is grown at 600 °C on a V-grooved substrate. Good photoluminescence properties are observed from the grown QWR, with the peak energy being in good agreement with the calculated energy level of a parabolic shape lateral confinement potential. © 1995 American Institute of Physics.

Selective area epitaxial growth on a nonplanar substrate is one of the most intensively investigated techniques of fabricating high quality semiconductor quantum wires (QWRs) or quantum dots (QDs). Successful laser operation has been achieved with a metalorganic chemical vapor deposition (MOCVD) grown AlGaAs/GaAs QWR on a V-grooved substrate as the active layer. This method depends on the lateral variation of growth rate on nonplanar substrates due to the different migration length of group III species on different crystalline facets. Therefore, a high selectivity of growth rate is desired to obtain ideal QWR or QD structures. For this purpose, a high growth temperature (≥700 °C) and a low V/III ratio are generally used to realize a high selectivity because such conditions can enhance the migration of group III species. However, high growth temperature is not suitable for the fabrication of QWR or QD structures for electron device applications, since a growth temperature higher than 700 °C usually leads to the increase of residual impurities in MOCVD growth. The lowest impurity concentration and highest carrier mobility are obtained at the temperature range of 600–650 °C. Therefore, fabrication of QWR or QD structures at the temperature range of 600–650 °C is required when considering electron devices utilizing QWR or QD structures.

In this letter, we report the successful growth of high quality AlGaAs/GaAs QWRs by using flow rate modulation epitaxy (FME) at a growth temperature as low as 600 °C. The FME method was first developed by Kobayashi et al. for low-temperature MOCVD growth of GaAs and was recently extended to the growth of other III–V semiconductors. Figure 1(a) shows the typical gas flow sequence of the FME growth. In FME growth, group III and group V gases, triethylgallium (TEGa) and AsH₃ in this work, are supplied alternatively to the substrate surface. To prevent evaporation of arsenic and impurity incorporation during TEGa flow period, a very small amount of AsH₃ indicated by r₀ is supplied throughout the growth. Due to the extremely low arsenic partial pressure during the TEGa flow period, Ga species can migrate very rapidly on the substrate surface, which is considered very important for the formation of QWRs. At a growth temperature of 550 °C, GaAs epitaxial layers with crystalline quality higher than that of GaAs grown by conventional MOCVD have been reported by the use of FME. The FME method is different essentially from atomic layer epitaxy (ALE) because the growth is not self-limited.

The epitaxial growth was carried out using a horizontal MOCVD system at 76 Torr. TEGa, trimethylaluminum (TMAI) and AsH₃ (20% in H₂) were used as group III and group V sources, respectively. The substrates used were (001) oriented semi-insulating GaAs. Two kinds of patterned substrates were formed by photolithograph and wet chemical etching, one is the forward mesa substrate for the investigation of growth selectivity, and the other the V-grooved substrate for the growth of QWR, both with the patterned stripes aligned in the [01 ¯ 1] direction. The pattern pitch is 100 μm. The top width and the depth were about 3 and 2 μm for the

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FIG. 1. (a) Typical gas flow sequence of FME. (b) Gas flow sequence used in this work.
FIG. 3. Growth rate ratio ~measuring the PL full width at half-maximum an Al 0.39 Ga 0.61 As/GaAs single quantum well

MESA pattern and 6 and 4 μm for the V-grooved pattern, respectively. The growth temperature was varied from 550 to 790 °C for the conventional MOCVD growth and kept constant at 600 °C for the FME growth. A V/III ratio of about 137 was used in MOCVD growth. The gas flow sequence actually used in FME growth is shown in Fig. 1(b). A H2 purge period with the duration of 1 s was inserted between the TEGa and AsH3 flow periods compared with Fig. 1(a) to avoid gas mixing. The total amounts of TEGa and AsH3 supplied in one flow period were about 2.83×10⁻² and 2.98 μmol, respectively. The above conditions gave a growth rate of about 0.6 monolayer (ML)/cycle on flat substrates. The small amount of AsH3 (r0) was supplied with a different AsH3 line from that used for the AsH3 flow period to achieve rapid gas exchange. The optical properties of the grown structures were characterized by low-temperature photoluminescence (PL) measurements with the 5145 Å line of an Ar⁺ laser as the excitation source. The laser spot diameter was about 190 μm.

It is reported that the small amount of AsH3 (r0) affects significantly the electrical and optical properties of the grown layers. Here, we first optimized the flow rate of r0 by measuring the PL full width at half-maximum (FWHM) of an Al0.39Ga0.61As/GaAs single quantum well (SQW) grown with different values of r0. The SQW samples were grown at 600 °C on unpatterned flat substrates. The layer structures of the SQW samples are as follows: a 300 nm thick GaAs buffer layer, a 300 nm thick bottom AlGaAs barrier layer, a 7 nm thick GaAs well layer, a 150 nm thick top AlGaAs barrier layer, and a 30 nm thick GaAs cap layer. Only the GaAs well layer was grown by FME, with all the other layers grown by conventional MOCVD. Figure 2 shows the FWHM of the grown SQW as a function of the flow rate of r0. Like the results of Yamauchi et al. there exists an optimized value of r0 at which the FWHM shows a minimum value. The smallest FWHM obtained here is 9 meV for a r0 value of 0.89 μmol/min. It is worthy to mention that the FWHM of 9 meV is narrower than that of the SQW grown by MOCVD at 600 °C (13.3 meV), which indicates that FME gives a better crystalline quality than the conventional MOCVD at such a low growth temperature. The optimized value of r0 of 0.89 μmol/min was used in the following experiments.

Before growing QWRs, we first investigated the growth selectivity of FME in contrast to the conventional MOCVD. The growth selectivity is defined as the ratio of the growth rate on (001) mesa top region to that on (111)A sidewall, i.e., R(001)/R(111)A, as shown in the inset of Fig. 3. For this purpose, Al0.39Ga0.61As/GaAs multilayers were grown at different temperatures with different growth methods and the grown thicknesses were measured using scanning electron microscopy (SEM). Figure 3 shows the selectivity as a function of growth temperature. In the conventional MOCVD growth, the growth rate on the (001) mesa top plane is generally larger than that on the (111)A plane due to the migration of Ga species from the (111)A sidewall to the (001) mesa top at the temperature range of 550–790 °C. The growth rate ratio, that is the growth selectivity, increases with increasing growth temperature as expected. However, at the growth temperature of 600 °C, the growth rate on the (001) mesa top plane is only about 1.34 times higher than that on the (111)A plane. By the use of FME, the growth rate ratio is increased to 2.9, an enhancement by a factor as large as 2.2 against the case of MOCVD at 600 °C. Moreover, the selectivity of FME at 600 °C is even larger than that of conventional MOCVD at 790 °C. The great enhancement of selectivity by the use of FME could be attributed to the enhanced migration of Ga species, as compared with the case of conventional MOCVD.

Based on results obtained above, a QWR structure was grown on the V-grooved substrate. The layer structure of the QWR sample is the same as that of the sample used in Fig. 2, and was given again in Fig. 4(a). The layer thickness and Al composition are nominal values on the (001) flat substrate. In this sample, the GaAs well layer was grown by FME at 600 °C, while all the other layers were grown by MOCVD at a slightly higher temperature of 650 °C to prevent the deterioration of the crystalline quality of the AlGaAs barrier layer. Figure 4(b) shows the transmission electron microscopy (TEM) image of the cleaved cross section of the grown...
sample taken along the [011] direction. A crescent shaped QWR structure with a central thickness of about 9 nm and a lateral width of about 28 nm was clearly observed at the bottom of the V-groove. The (111)A sidewall QWL thickness was about 3.3 nm at the region observed by TEM which is about 450 nm away from the V-groove bottom. At the region far away from the V-groove, the (111)A sidewall QWL thickness was estimated to be slightly thicker than 3.3 nm from SEM observation of the thick layer sample. The lateral width of the QWR is considerably smaller than that of the generally reported crescent shape QWR grown by conventional MOCVD at high temperature.\(^9,10\) A small lateral width is expected be able to provide a better quantum confinement.

Figure 5 shows the low-temperature (10 K) PL spectrum of the grown QWR. For PL measurements, the top (001) QWLs between V grooves were removed selectively by wet chemical etching. Peaks at 819 and 831 nm are due to the luminescence from GaAs bulk layer. The luminescence peaks at 750 and 763 nm are those from the (111)A sidewall QWLs with different well thicknesses. The luminescence from QWR was observed as a weak peak at 789.5 nm with a FWHM of about 9.5 meV. The above identification of PL peaks has been confirmed by cathodoluminescence measurements. We also estimated the QWR transition energy following the procedure proposed by Kapon et al.\(^11\) We first calculated the confinement energies of QWL structures as a function of lateral position near the V-groove bottom using the TEM data. The lateral confinement potential could be fitted well with a parabolic profile, from which a series of QWR confinement energies with equal spacing were obtained. The energy spacings for the structure of Fig. 4(b) are calculated to be about 29.6 and 5.4 meV for electrons and heavy holes, respectively. Using the above energy values and assuming an exciton binding energy of 10 meV, we get a QWR transition energy between the first electron and heavy hole levels of 1.5811 eV. This value is in fairly good agreement with the observed QWR transition energy of about 1.5706 eV.

In summary, FME has been applied to low-temperature fabrication of AlGaAs/GaAs QWR structures on nonplanar substrates. The growth selectivity was found improved greatly by the use of FME, as compared with the conventional MOCVD. An AlGaAs/GaAs QWR with a central thickness of about 9 nm and a lateral width of about 28 nm was successfully formed on the bottom of a V-grooved substrate at a growth temperature as low as 600 °C. Good optical properties of the grown QWR structure were confirmed by PL measurements. These results suggest that FME is a very promising method for the fabrication of high quality QWRs or QDs, especially in cases where low-temperature growth is necessary.

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