Carrier capture efficiency of AlGaAs/GaAs quantum wires affected by composition nonuniformity of an AlGaAs barrier layer

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Effects of composition nonuniformity of an AlGaAs barrier layer on the carrier capture efficiency of an AlGaAs/GaAs quantum wire (QWR) grown on nonplanar substrates are investigated using photoluminescence measurements. The photogenerated carriers first experience a redistribution from the high Al composition region to the low Al composition region in the AlGaAs barrier layer due to the potential difference caused by the composition nonuniformity before they are captured by quantum well or QWR regions. Such a carrier redistribution greatly affects the carrier capture efficiency of QWR structures. © 1995 American Institute of Physics.

Many unique and important phenomena have been predicted to appear when the dimensionality of semiconductor quantum heterostructures, that is, the quantum well (QWL), the quantum wire (QWR), or the quantum dot (QD) are reduced from 2 to 1 or 0. For example, the performance of the conventional QWL laser is theoretically predicted to be greatly enhanced if the active layer is replaced by a QWR or QD structure. In optical devices, carrier capture from the adjacent barrier layer into the active layer plays an important role in determining the device performance. In AlGaAs/GaAs QWL structures, carriers can be effectively injected into the GaAs active layer from the AlGaAs barrier layer, which usually has a uniform alloy composition over the wafer surface. However, in the case of QWR or QD structures, the alloy composition of the barrier layer is not necessarily uniform over the wafer surface, depending on the fabrication technique. Selective area growth by metalorganic chemical vapor deposition (MOCVD) on the nonplanar substrate is a very effective method for the fabrication of high quality QWR or QD structures. Due to the different diffusion characteristics of Al and Ga species, a composition nonuniformity in the AlGaAs barrier could be expected. For example, when we grow AlGaAs on V-grooved substrates aligned along [011] direction, the Al composition on the (111)A sidewall is generally slightly higher than that on the (001) flat region because the Ga species can migrate more rapidly than the Al species from the (111)A sidewall to the (001) flat region. However, there are almost no reports on whether the composition nonuniformity of the AlGaAs barrier layer affects the carrier capture efficiency of QWR structures. In this letter, we investigated the effect of composition nonuniformity on the optical properties of an AlGaAs/GaAs QWR by observing the change of photoluminescence (PL) spectra after the removal of part of the AlGaAs barrier layer. It is found that the carrier capture efficiency of the QWR could be greatly affected by the composition nonuniformity of the AlGaAs barrier layer.

The QWR samples were grown by low pressure (76 Torr) MOCVD at a low growth temperature of 650 °C on V-grooved substrates. The V grooves, aligned along the [011] direction with a period of 4.8 μm, were formed on an (001) semi-insulating GaAs substrate by photolithography and wet chemical etching. Triethylgallium (TEGa), trimethylaluminum (TMAI), and AsH 3 were used as the group III and group V sources, respectively. Figure 1 presents a schematic illustration of the layer structure and the transmission electron microscopy (TEM) images of the cleaved cross section of the grown QWR sample which consists of the following layers: a 330 nm thick GaAs buffer layer, a 990 nm thick Al 0.33 Ga 0.67 As barrier layer, a 5 nm thick GaAs well layer, and a 160 nm thick Al 0.33 Ga 0.67 As barrier layer. Here, the layer thickness and the Al composition are all those for the layers grown on the (001) flat region. The GaAs QWR layer was grown by flow rate modulation epitaxy (FME), which could improve greatly the growth selectivity at low growth temperature. A low growth temperature is expected to give QWR structures with a low residual impurity concentration and a small lateral width. The resulting crescent-shaped QWR structure has a central thickness of 7.1 nm and a lateral...
width of about 31 nm. A slightly dark vertical stripe with a width of about 20 nm could be observed at the bottom of the V groove from the TEM image. This dark stripe, forming an AlGaAs/AlGaAs vertical quantum well (VQWL), resulted from the Ga-rich AlGaAs region due to the higher migration efficiency of the Ga species than that of the Al species from the (111)A sidewall to the bottom of the V groove.

Figure 2(b) shows the PL spectra of the grown sample measured at 10 K. The lower and upper parts of Fig. 2(b) are the spectrum for two samples taken from a single grown wafer: the as-grown sample and the sample from which parts of the (001) flat and the (111)A sidewall regions were removed selectively by wet chemical etching. The scanning electron microscopy (SEM) cross section image and the schematic illustration of the etched sample are presented in Fig. 2(a). In the schematic illustration, the dashed lines show the cross section of the sample before etching. After etching, the (001) flat QWL was completely removed and only part of the AlGaAs barrier layer remained on the (001) flat region. The spectra at the wavelength range of 600–680 nm which are mainly the luminescence from the AlGaAs barrier layers are magnified and replotted in Fig. 2(c). In these spectra, PL peaks originated from six different origins were observed, that is, the AlGaAs barrier layer, the (111)A sidewall QWL, the (001) flat QWL, the VQWL, the QWR, and the GaAs buffer layer. All of these PL peaks were identified from the layer thicknesses using the TEM image and indicated in Figs. 2(b) and 2(c). An important feature could be extracted from the comparison of the spectra of the as-grown sample with those of the etched sample: the PL peak intensities related to the (111)A sidewall and the bottom of the V groove, i.e., the high Al composition AlGaAs barrier layer (see below), the (111)A QWL, the VQWL, and the QWR, were significantly enhanced by the removal of parts of the (001) flat and the (111)A sidewall regions. In the case of the as-grown sample, the peak intensity of the (001) QWL is several times stronger than that of the (111)A sidewall related peaks, although the surface area of the (001) flat region is only about 36% of that of the (111)A sidewall region. In particular, luminescence from the QWR cannot be resolved in the spectrum of the as-grown sample, but can be clearly observed when parts of the (001) flat and the (111)A sidewall regions were removed. Moreover, the intensity of the QWR peak was found to depend drastically on the etching time. These results clearly indicate that carrier capture into the QWR is significantly impeded in the as-grown sample.

To understand the impediment of carrier capture by the QWR in the as-grown sample, we want to give a more detailed description of the spectra of the AlGaAs barrier layer in Fig. 2(c). In the spectrum of the etched sample, luminescence from two AlGaAs layers with different Al compositions could be resolved. The Al compositions were calculated to be x=0.393 and 0.335 from the band edge emission peaks at 617 and 640 nm. The broad peaks at 625.2 and 645 nm are the impurity emission peaks of the x=0.393 and 0.335 AlGaAs layers. The high and low Al composition layers are attributed to AlGaAs layers on the (111)A flat and (001) flat region, respectively. The composition nonuniformity of the AlGaAs barrier layers is considered to be the result of the higher migration efficiency of the Ga species than that of the Al species from the (111)A sidewall plane to the (001) flat plane and the bottom of the V groove as mentioned above. In the case of the as-grown sample, an additional peak corre-
sponding to an Al composition of \(x=0.347\) was also observed, which might be that formed at the connecting region of the (111)A and the (001) plane. The small wavelength deviation of the (001) AlGaAs \((x=0.328)\) layer of the as-grown sample from that of the etched sample may be due to the superimposition of the \(x=0.328\) AlGaAs band edge peak with the impurity peak of the \(x=0.347\) layer or some growth fluctuation over the substrate surface. Like the trend of QWL and QWR emission peaks, in the as-grown sample, the (111)A sidewall AlGaAs peak intensity is much weaker than that of the (001) flat region AlGaAs peak, in spite of the fact that the (111)A sidewall plane has an area nearly 3 times larger than that of the (001) flat plane.

The change of the relative intensities of the (111)A sidewall-related peaks and the (001) flat region-related peaks by the removal of part of the (111)A sidewall and (001) flat region suggests that there occurred a redistribution of the photogenerated carriers from the (111)A sidewall to the (001) flat region before they recombined in the various regions. One possibility is that the photogenerated carriers in the AlGaAs barrier layers first fall into the (111)A and (001) QWLS, and part of the carriers diffused from the (111)A sidewall QWL into the (001) QWL which has a thicker well thickness and thus a lower quantum energy level. This kind of carrier redistribution was proposed by Christen et al. from a time-resolved cathodoluminescence study of QWR grown on V-grooved substrates. However, such a carrier diffusion is not likely to occur in our present sample. The TEM cross section observation shows that GaAs well layer thickness around the connection corner between the (001) flat and (111)A sidewall facets is extremely thin. Therefore, there exists a high potential barrier between the (111)A and the (001) QWLS that makes the carrier diffusion from the (111)A QWL to the (001) QWL impossible. We proposed that the photogenerated carriers first redistributed in the AlGaAs barrier that has a composition nonuniformity and then were captured by the various QWL and QWR regions where they recombined. The energy gap difference between the (111)A sidewall \((x=0.393)\) and the (001) flat region \((x=0.335)\) AlGaAs layer is calculated to be about \(\Delta E_c=72.3\) meV. This band gap difference gives a band discontinuity for the conduction band \((\Delta E_c)\) and the valence band \((\Delta E_v)\) of 44.8 and 27.5 meV, respectively, assuming a \(\Delta E_c=62\% \Delta E_g\) rule.9 The band diagram of the AlGaAs barrier layer at different positions of the V-groove substrate and the situation of the carrier redistribution are illustrated in Fig. 3. The consideration of carrier redistribution in the AlGaAs barrier layer is reasonable since the band discontinuity between the (111)A sidewall and the (001) flat region AlGaAs layers is much larger than the thermal energy at 10 K. In the case of the etched sample, such carrier redistribution is prevented because the (111)A sidewall AlGaAs is completely separated from the (001) AlGaAs layer. From the large intensity ratio of (001) to (111)A QWL peak in the as-grown sample, the process of carrier redistribution in the AlGaAs barrier layer is much faster than the process of carrier capture into (111)A QWL directly. The time scale of this carrier redistribution could be roughly estimated from the PL spectrum of the as-grown sample:

\[
\frac{I_{QWL}^{(111)A}}{I_{QWL}^{(001)}} = \left( \frac{\tau_1}{\tau_2} \right) F_{geom},
\]

where \(I_{QWL}^{(111)A}\) and \(I_{QWL}^{(001)}\) are the integrated PL intensity of the (111)A sidewall and the (001) flat QWL, respectively, \(\tau_1\) and \(\tau_2\) are the carrier transition time from the (111)A sidewall AlGaAs barrier layer to the (001) flat AlGaAs layer and that from the (111)A sidewall AlGaAs layer to the (111)A QWL, and \(F_{geom}\) is a geometrical factor given by the area ratio of the (111)A QWL and the (001) QWL \((\sim 2.8\) for the present sample). In Eq. (1), the luminescence from the AlGaAs barrier layer and the nonradiative recombination processes have been ignored. Using the PL spectra in Fig. 2(b), we get \(\tau_1 = (1 - \frac{1}{r}) \tau_2\). A trapping time of about 50 ps was reported for a 5 nm thick AlGaAs/GaAs QWL. Therefore, the carrier redistribution in the AlGaAs barrier layer probably occurs on a time scale shorter than 10 ps.

In summary, we have investigated the effects of composition nonuniformity of the AlGaAs barrier layer on the carrier capture efficiency of an AlGaAs/GaAs QWR grown on V-grooved substrates. We have shown that photogenerated carriers redistribute in AlGaAs barrier layers before they are captured into QWL or QWR regions due to the potential difference produced by Al composition nonuniformity. This carrier redistribution process can affect markedly the carrier capture efficiency of QWR. These results are considered to be very important in optical device applications utilizing QWR structures grown on nonplanar substrates.

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