AlGaAs/GaAs quantum wires with high photoluminescence thermal stability

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We report a 5 nm thick V-shaped AlGaAs/GaAs single quantum wire (QWR) that showed high photoluminescence (PL) thermal stability as a result of our recent progress in fabrication techniques. The integrated PL intensity of the QWR sample was quenched only by a factor of about 2.5 when the temperature was increased from 5 to 300 K. This sample also showed higher PL thermal stability over the whole temperature range than a 5 nm thick single quantum well reference sample grown under similar conditions. © 2003 American Institute of Physics. [DOI: 10.1063/1.1633679]

Semiconductor quantum wires (QWRs) have been predicted to show various superior optical and electronic properties compared with their higher-dimensional counterpart: quantum wells (QWLs).1,2 Despite the large number of experimental works devoted to the realization of high-quality QWRs over the past two decades,3 it remains difficult to obtain effects from QWRs superior to those typically observed from QWLs. A few years ago, we developed a QWR fabrication technique: the use of flow rate modulation epitaxy (FME) in selective growth of AlGaAs/GaAs on V-grooved substrates.4,5 This gave rise to significant improvements in wire quality over conventional techniques, and we were able to demonstrate several superior optical effects that originated from the one dimensionality of QWRs, including smaller thermal broadening of the photoluminescence (PL) linewidth (a much narrower PL linewidth at room temperature) than that of a QWL,6 and weaker temperature dependence of the laser threshold current.7 Very recently, we developed two other techniques: the use of a new arsenic source material [tertiarybutylarsine (TBAs)] and an improved V-groove stripe alignment process. These techniques further improved the wire quality in a dramatic way, especially in terms of interface quality8,9 and crystal purity.10 We found that the use of TBAs can greatly reduce the concentration of nonradiative recombination centers around the QWR compared with growth using AsH3; the room-temperature integrated PL intensity of a 5 nm TBAs-grown QWR was more than 3000 times stronger than that of a 5 nm AsH3-grown sample.10 TBAs can also suppress step bunching on the high-index (311)A facets of QWRs as revealed by atomic force microscope observation and thus improve the interface uniformity.8 On the other hand, use of the V-groove stripe alignment process during photolithography allows us to align the V grooves to the exact [01-1] crystallographic direction with precision greater than 3.7×10⁻³ deg. This is improvement of approximately 27-fold over our old fabrication process. We have characterized the interface quality of our new-generation QWRs using scanning micro-PL measurements.9 We show in Fig. 1 a typical scanning micro-PL intensity image of a 5 nm QWR sample grown using these improved techniques measured at 10 K. In this case, the wires are essentially an assembly of real one-dimensional monolayer-step islands whose average lengths were estimated to be about 0.4 μm by statistically analyzing their micro-PL images.9 The longest islands can be as long as a few microns like, for example, the one at Z=5 μm shown in Fig. 1. This is in striking contrast to our old-generation QWRs which showed monolayer thickness fluctuation on the order of 20–100 nm.11 Moreover, the PL peak of each of these one-dimensional islands can be fitted perfectly by a single Lorentizan curve, suggesting that excitonic states are coherently extended in these islands.9 In this letter, we report

![FIG. 1. Scanning micro-PL intensity image of a new-generation 5 nm AlGaAs/GaAs QWR measured at 10 K. The image was obtained by scanning the microscope objective lens along the wire axis on the sample surface and recording the micro-PL spectrum at each position. The spatial resolution of the micro-PL system was about 1 μm.](image-url)
higher PL thermal stability observed from these new-generation QWRs compared with QWLs grown under similar conditions.

The QWR sample studied in this work was grown at 630 °C by a low-pressure metalorganic vapor phase epitaxy (MOVPE) system. Trimethylaluminum, triethylgallium, and TBAs were used as group III and group V precursors, respectively. More details on the growth conditions can be found in previous work.5,8 The V grooves, with a pitch of 4 μm, were formed on (001)-oriented GaAs substrates by standard photolithography and wet chemical etching procedures. The sample structure consists of a 0.3 μm GaAs buffer layer, a 0.9 μm Al0.42Ga0.58As lower barrier layer, a FME-grown 5 nm GaAs QWR layer, a 0.2 μm Al0.42Ga0.58As upper barrier layer, and a 10 nm GaAs cap layer. For comparison, a 5 nm single QWL with a similar layer structure was also grown under similar conditions.

The luminescence thermal stability of the QWR sample was characterized by temperature-dependent PL measurements. The sample was fixed on the cold finger of a He-flow cryostat whose temperature was controlled within accuracy of ±0.5 K. A continuous wave (cw) Ti:sapphire laser was focused onto the sample surface to a spot size of about 100 μm at power of about 10 mW. The laser wavelength (700 nm at 5 K) was tuned to be between the emission wavelength of the QWR and that of the sidewall QWL (~680 nm at 5 K) so as to excite the QWR selectively. The excitation wavelength was also adjusted with increasing temperature to maintain a constant energy separation (140 meV) of the excitation laser from the PL emission position in order to avoid possible change in the laser absorption coefficient at high temperatures. The PL signal was detected with a Jobin-Yvon 64 cm triple monochromator and a liquid nitrogen-cooled charge coupled device camera.

Figures 2(a) and 2(b) show the PL spectra of the QWR and the QWL reference samples measured in a temperature range of 5–300 K, respectively. At 5 K, the PL peak from the QWR was observed around 1.63 eV with a full width at half maximum (FWHM) of about 9 meV. A weak shoulder, indicated by a vertical arrow in Fig. 2(a), was also observed with an energy separation of about 15.5 meV from the main peak. The intensity of this peak was very sensitive to the temperature; it disappears completely at 20 K. A similar peak was sometimes observed in the new-generation QWR samples, but its origin was not very clear. It is surprising to observe that the PL can be measured easily up to room temperature (~300 K) without changing any measurement conditions. The 5 nm QWL reference sample showed a ground state emission peak at 1.624 eV at 5 K with a FWHM of about 8.8 meV. We then calculated the integrated PL intensity of these spectra in order to evaluate the luminescence thermal stability. Figure 3 shows the integrated PL intensity of the QWR as a function of the temperature together with the results from the 5 nm QWL reference sample for comparison, in which the PL intensities were normalized by the values at 5 K.

The integrated PL intensity of the 5 nm QWR first showed a weak increase, followed by a weak decrease, with an increase in temperature in the range of 5–50 K, then became independent of the temperature up to 130 K. The PL intensity started to decrease slowly with further increases in temperature beyond 130 K, indicating that scattering of excitons by nonradiative recombination centers begins to take effect from 130 K. It is remarkable to notice that the overall quenching of the integrated PL intensity from 5 to 300 K is
In summary, we reported a 5 nm AlGaAs/GaAs V-shaped QWR that showed very high PL thermal stability for a QWR as a result of our recent progress in fabrication techniques. The integrated PL intensity of the QWR sample was quenched only by a factor of 2.5 from 5 to 300 K. This QWR showed a higher PL thermal stability than an equivalent QWL sample, and was tentatively considered an intrinsic effect of a high-quality QWR. These results suggest that the QWR as a material for high-efficiency optoelectronic devices is superior to a conventional QWL structure.

The PL intensity of a semiconductor quantum structure is considered to be determined by three factors: (1) the radiative recombination rate, (2) the concentration of nonradiative recombination centers, and (3) the scattering rate of excitons/free carriers by nonradiative recombination centers. A V-grooved QWR is usually surrounded by three crystallographic facets: one (001) facet at the center and two {311}A facets on the two sides. A {311}A facet is unlikely to give rise to a lower concentration of nonradiative recombination centers compared with growth on the (001) surface in MOVPE. We tentatively attributed the higher PL thermal stability observed in our new-generation QWR sample to a higher radiative recombination rate and/or a lower exciton/free-carrier scattering rate by nonradiative recombination centers in QWRs than in QWLs. In other words, what we observed is most likely an intrinsic effect of a high-quality QWR. A higher PL thermal stability is also an effect theoretically expected for a high-quality QWR. First, a higher radiative recombination rate is expected from a QWR than from a QWL due to the square root dependence on the temperature of the radiative recombination lifetime of a QWR compared with the linear dependence of that of a QWL. Second, a lower longitudinal optical (LO) phonon scattering rate for excitons and free carriers was also predicted theoretically for a QWR compared with a QWL. However, further experiments are necessary to confirm the above speculations.

In summary, we reported a 5 nm AlGaAs/GaAs V-shaped QWR that showed very high PL thermal stability for a QWR as a result of our recent progress in fabrication techniques. The integrated PL intensity of the QWR sample was quenched only by a factor of 2.5 from 5 to 300 K. This QWR showed a higher PL thermal stability than an equivalent QWL sample, and was tentatively considered an intrinsic effect of a high-quality QWR. These results suggest that the QWR as a material for high-efficiency optoelectronic devices is superior to a conventional QWL structure.