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We report on the optical properties of threefold stacked InGaAs sidewall quantum wires (QWires) with quaternary InGaAsP barriers grown on shallow-patterned InP (311)*A* substrates by chemical beam epitaxy. Temperature dependent photoluminescence (PL) reveals efficient carrier transfer from the adjacent quantum wells (QWells) into the QWires at low temperature, thermally activated repopulation of the QWells at higher temperature, and negligible localization of carriers along the QWires. Strong broadening of power dependent PL indicates enhanced state filling in the QWires compared to that in the QWells. Clear linear polarization of the PL from the QWires confirms the lateral quantum confinement of carriers. These results demonstrate excellent optical quality of the sidewall QWire structures with room temperature PL peak wavelength at 1.55 μm for applications in fiber-based optical telecommunication systems. © 2006 American Institute of Physics. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2199088]

I. INTRODUCTION

The strong interest in low-dimensional semiconductor structures originates from the lateral quantum confinement of carriers leading to novel basic physics phenomena and device applications. In quantum wires (QWires) the lateral quantum confinement leads to a peaked energy dependence of the density of states (DOS) resulting in enhanced optical efficiency and nonlinearity and in linear polarization of the emission due to valence-band mixing at the center of the Brillouin zone.[1] To fabricate well-defined QWires, various techniques are pursued. Self-assembled QWires are most easy to fabricate, but their size, density, position, and uniformity are difficult to control.[2,3] Position-controlled and uniform QWires have been realized by selective growth on V-groove or ridge-patterned low-index substrates.[4,5] It is based on preferential adatom migration away from slow-growing sidewalls to the bottom of the V-groove or the top of the ridge. A complementary concept for the formation of QWires is selective growth on shallow-patterned high-index substrates. On shallow [01-1] mesa-patterned GaAs (311)*A* substrates, preferential adatom migration towards the mesa sidewall in the sector towards the next (100) plane occurs to produce quasi-planar lateral QWires. The direction of adatom migration towards the fast-growing mesa sidewall is, thus, opposite to that on patterned low-index substrates for formation of V-groove or ridge-type QWires. The quasi-planar growth provides high material quality and uniformity while the strong growth selectivity ensures strong lateral carrier confinement in these sidewall QWires.[6,7]

Recently, we have fabricated highly uniform InGaAs sidewall QWires in InGaAsP on shallow [01-1] mesa-patterned InP (311)*A* substrates. Preferential migration of In and Ga adatoms towards the mesa sidewall produces QWires with thickness enhancement by a factor of 1.2-1.3 and 4% enrichment of the In composition compared to that of the adjacent lattice-matched InGaAs quantum wells (QWells). The width of the tapered QWires is about 200 nm, which has been determined by cross-sectional scanning tunneling microscopy (X-STM) and photoluminescence (PL) measurements.[8] Here we present detailed temperature, power, and polarization dependent PL measurements of the threefold stacked InGaAs sidewall QWires with room temperature (RT) PL peak wavelength at 1.55 μm required for applications in fiber-based optical telecommunication systems. Efficient carrier transfer from the QWells into the QWires at low temperature, thermally activated repopulation of the QWells at higher temperature, negligible carrier localization along the QWires, and enhanced state filling in the QWires is deduced from temperature and power dependent PL. Lateral quantum confinement of carriers in the QWires is confirmed by a clear linear polarization of the PL.

II. EXPERIMENT

The QWire structure selected for the present study was grown by chemical beam epitaxy (CBE) using trimethylindium (TMIn), triethylgallium (TEGa), AsH_3, and PH_3 as precursors. The AsH_3 and PH_3 gases were thermally decomposed in a high-temperature injector at 900 °C. The InP (311)*A* substrate was patterned into [01-1] oriented mesa stripes with 2 μm width, 4 μm pitch, and 35 nm height. The substrate was mounted by indium on a Mo block, and degassed in the buffer chamber at 200 °C for 30 min before being transferred into the growth chamber. The layer structure consisted of a 20 nm InP plus 20 nm lattice-matched $In_{0.73}Ga_{0.27}As_{0.59}P_{0.41}$ buffer with band gap at 1.3 μm (*Q*1.3 InGaAsP) which was followed by three 3 nm thick lattice-matched $In_{0.53}Ga_{0.47}As$ layers separated and overgrown by 50 nm lattice-matched *Q*1.3 InGaAsP. The growth temperature was 500 °C and the growth rates were 0.767 ML/s for

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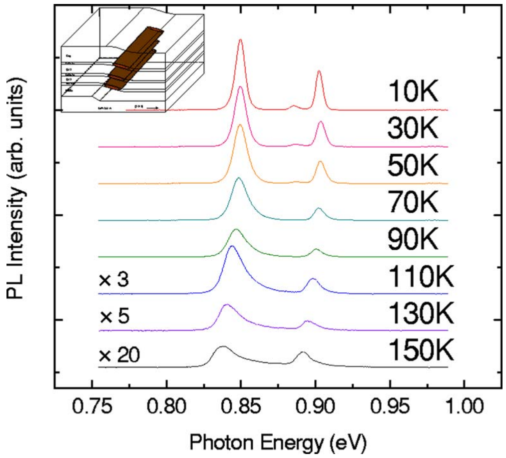

FIG. 1. (Color online) PL spectra of the QWires and QWells as a function of temperature. The inset shows a schematic drawing of the QWire structure.

InGaAs and 0.522 ML/s for InGaAsP. For PL, the sample was placed in a He-flow cryostat and excited by the 532 nm line of a Nd:yttrium aluminum garnet (YAG) laser at temperatures between 10 K and RT and excitation power density between 2.5 and 250 mW/cm^2. The PL was dispersed by a single monochromator and detected by a cooled InGaAs charge-coupled device. A linear polarizer followed by a quarter-wave plate was inserted in the detection path directly after the sample to analyze the linear polarization of the PL.

III. OPTICAL PROPERTIES

A. Temperature dependent PL

Figure 1 shows a series of PL spectra as a function of temperature. The excitation power density is 250 mW/cm^2. A schematic drawing of the QWire structure is depicted in the inset. The line at lower energy is from the QWires at the fast-growing mesa sidewall and that at higher energy from the adjacent QWells. The weak line in between stems from the opposite slow-growing mesa sidewall which quickly smears out during growth.[8] At low temperature, the PL lines of the QWires and QWells are well separated, allowing one to accurately determine the PL intensity and peak energy. At higher temperature the PL intensity and peak energy are determined by line fitting. With increase of the temperature from 10 to 60 K, the integrated PL intensity of the QWires increases while that of the QWells decreases, as plotted in Fig. 2(a). The emission from the slow-growing sidewall vanishes. The total integrated PL intensity stays almost constant. This reveals efficient carrier transfer from the QWells and the slow-growing sidewall to the QWires upon temperature rise, which is attributed to thermally activated delocalization of carriers in the QWells and at the slow-growing sidewall, and the intrinsic increase of the carrier diffusion length $L = \sqrt{D\tau}$ in the QWells in this temperature range.[9] D is the carrier diffusion constant and τ the lifetime.

Above 80 K, the integrated PL intensity of the QWires decreases relative to that of the QWells, which is depicted in Fig. 2(b) by the ratio of QWell to QWire integrated PL intensity as a function of temperature, undergoing a minimum

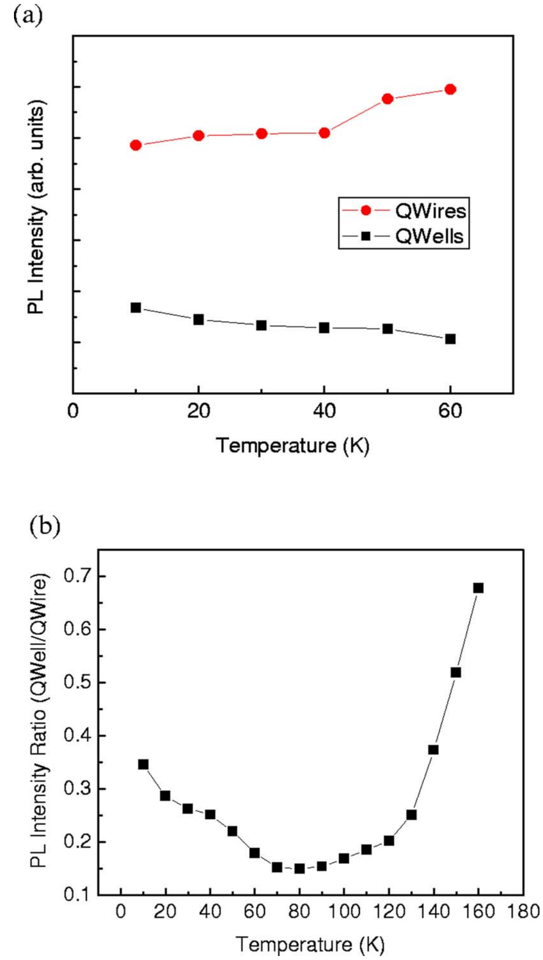

FIG. 2. (Color online) (a) Integrated PL intensity of the QWires (●) and QWells (■), and (b) intensity ratio of the PL from the QWells and QWires as a function of temperature.

around 80 K. This reflects the decrease of the carrier diffusion length at higher temperature and, more important, thermally activated repopulation of the QWells, similar to the case of GaAs sidewall QWires.[9] The total PL intensity decreases above 60 K up to RT by about three orders of magnitude due to the thermally activated transfer of carriers to the InGaAsP barriers, generally observed for QWells, QWires, and quantum dots (QDots). The ratio of QWell to QWire integrated PL intensity increases to about two at RT.[8]

The temperature dependence of the PL peak energy of the QWires shown in Fig. 3 almost perfectly follows the temperature dependence of the band gap energy after Ref. 10 (solid line in Fig. 3). Only a very weak indication of an S-shapelike dependence is observed. S-shapelike temperature dependence originates from the thermally activated carrier delocalization in the presence of potential fluctuations due to inhomogeneities in size and composition of QWells, QWires, or QDots.[11] The preferential population of lower-energy sites results in enhanced low-energy shift of the PL peak at intermediate temperatures. Hence, the absence of such S-shapelike temperature dependence of the PL peak energy demonstrates high uniformity of the present QWire structure along the mesa sidewall.

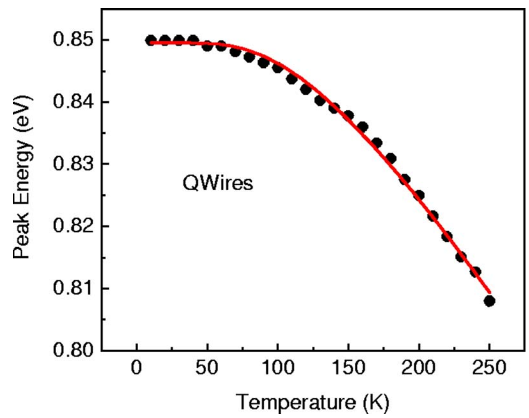

FIG. 3. (Color online) Temperature dependence of the PL peak energy of the QWires.

B. Power dependent PL

Figures 4(a) and 4(b) show the power dependent PL spectra of the QWires and QWells taken at low temperature (10 K). With increase of the excitation power density from 2.5 to 250 mW/cm^2, the full width at half maximum (FWHM) of the QWires broadens by 8 meV while that of QWells remains unchanged, as plotted in Fig. 5(a). Moreover, the PL peak energy of the QWires shifts to higher energy by 4 meV while it stays constant for the QWells in the excitation power density range under consideration [Fig. 5(b)]. In the present QWire structure, piezoelectric effects can be neglected to account for the PL high-energy shift due to the small lattice mismatch of less than 0.3%.[12,13] This is confirmed by the fact that the low-energy side of the PL spectra is unchanged, and the PL spectra broaden towards higher energy. Hence, we conclude that the observed broadening and high-energy shift of the PL from the QWires with excitation power density is due to enhanced state filling in the QWires compared to that in the QWells reflecting the transition from the two-dimensional steplike DOS of QWells to the one-dimensional peaked DOS of QWires.

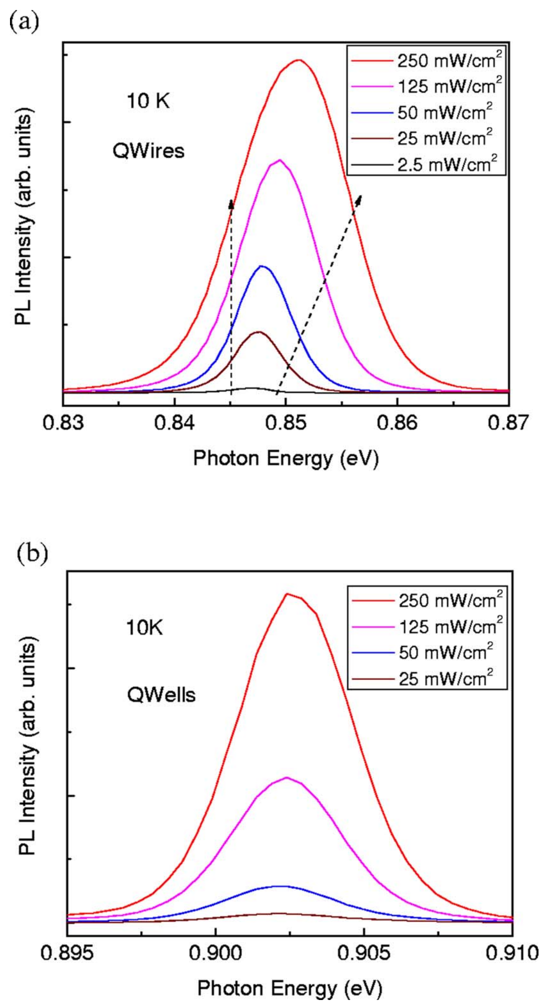

FIG. 4. (Color online) Excitation power density dependent PL spectra (a) of the QWires and (b) of the QWells taken at 10 K.

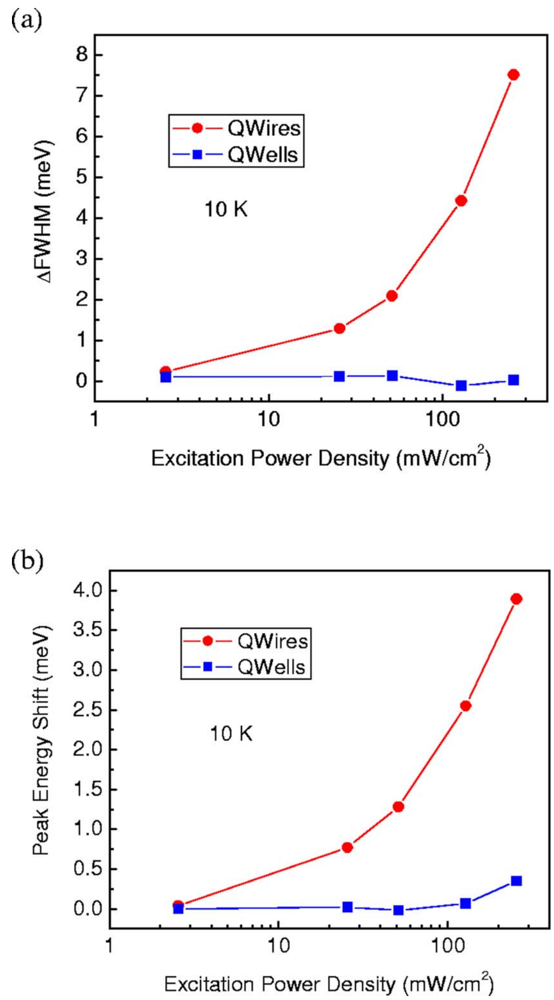

FIG. 5. (Color online) (a) Increase of the full width at half maximum (△FWHM) of the PL from the QWires (●) and QWells (■), and (b) PL peak energy shift of the QWires (●) and QWells (■) as a function of excitation power density at 10 K.

C. Linear polarization dependent PL

Linear polarization dependent PL spectra of the QWires and QWells taken at low temperature and RT are depicted in Figs. 6(a) and 6(b). The excitation power density is 250 mW/cm^2. In the spectra taken at low temperature, the PL from the QWires (PL peak at 0.85 eV) is clearly polarized along the [01-1] direction, i.e., along the QWire axis,

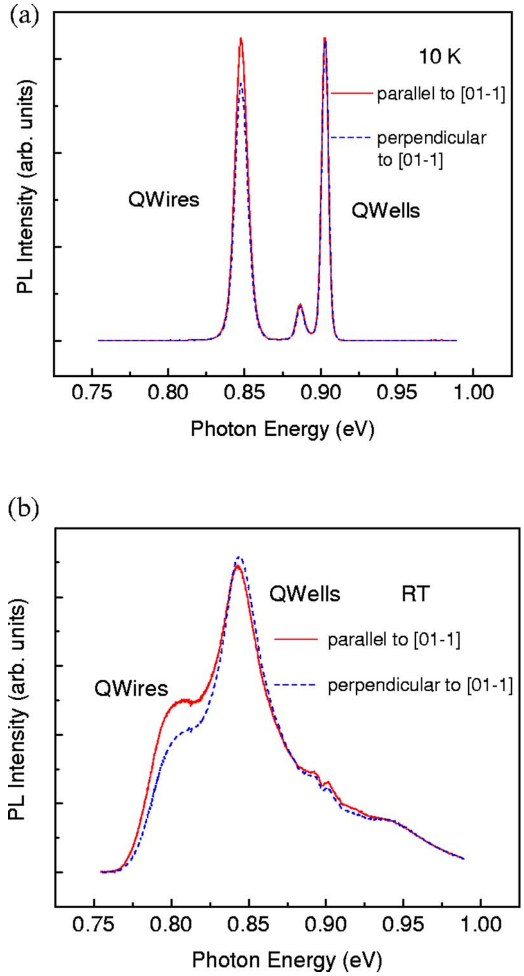

FIG. 6. (Color online) Linear polarization dependent PL spectra taken (a) at 10 K and (b) at room temperature (RT). The solid and dashed lines indicate the linear polarization along and perpendicular to the QWire axis.

whereas the polarization of the PL from the QWells and from the smeared-out slow-growing mesa sidewall (small peak in-between) is negligible. The degree of linear polarization of the PL from the QWires, defined as $(I_{\parallel}-I_{\perp})/(I_{\parallel}+I_{\perp})$ is 0.09. At RT, the degree of linear polarization of the PL from the QWires is increased to 0.13 [PL peak at 0.80 eV in Fig. 6(b)]. This evidences that the polarization anisotropy of the PL from the QWires is of intrinsic nature and not, e.g., related to anisotropic localization sites effective at low temperature. For the QWells, the electron-heavy hole transition [PL peak at 0.85 eV in Fig. 6(b)] reveals a weak degree of linear polarization of −0.03 along [2-3-3] while the electron-light hole transition (0.90 eV) is weakly polarized along [01-1] due to the valence band anisotropy in the (311) plane.[14] The PL of the bulk InGaAsP barriers (0.95 eV) is unpolarized. The linear polarization anisotropy of the PL from the QWires is in agreement with lateral quantum confinement effects, causing a mixing of the heavy-hole and light-hole energy states. Before a definite conclusion, however, other possible contributions have to be discussed.

The presence of biaxial compressive strain in the QWires, i.e., in-plane lattice compression such as in strained QWells, in itself does not create polarization anisotropy. It rather decreases linear polarization effects by increasing the energy separation between heavy-hole and light-hole states. The piezoelectric field induced by the biaxial compressive strain in the QWires has an in-plane component along the [2-3-3] direction, i.e., perpendicular to the QWire axis.[13] Hence, the effect of the piezoelectric field is to induce linear polarization perpendicular to the QWires which is perpendicular to the observed one. Moreover, due to the small lattice mismatch of less than 0.3%, pronounced piezoelectric effects are not expected or observed in the power dependent PL measurements. Triaxial strain in the QWires, i.e., including (nonuniform) strain perpendicular to the QWire axis, can cause linear polarization of the PL along the QWires. However, again due to the small lattice mismatch, it cannot account for the observed magnitude.[12] Electromagnetic (grating) effects can be excluded due to the quasi-planar QWire structure and would affect the QWire and QWell PL similarly.[15] Therefore, we conclude that the linear polarization of the PL from the QWires indeed stems from lateral quantum confinement. It is interesting to note that the relatively strong degree of linear polarization indicates an effective width of the lateral extension of the ground state wave function in the QWires of less than 100 nm.[16,17] This is considerably smaller than the geometrical width of the QWires of 200 nm deduced by X-STM. The effective QWire width is determined by the precise lateral In composition profile and thickness change, which are difficult to evaluate by X-STM, and is easily reduced compared to the geometrical width of these laterally tapered QWire structures.

IV. CONCLUSIONS

In conclusion, we have investigated the optical properties of stacked InGaAs sidewall quantum wires (QWires) with quaternary InGaAsP barriers grown on shallow-patterned InP (311)*A* substrates by chemical beam epitaxy (CBE). The temperature dependent integrated photoluminescence (PL) intensity indicated efficient carrier transfer from the adjacent quantum wells (QWells) into the QWires at low temperature and thermally activated repopulation of the QWells at higher temperature. The dependence of the PL peak energy on temperature showed negligible localization of carriers along the QWires, indicating high uniformity in size and composition. Power dependent PL revealed strong broadening and high-energy shift of the QWire PL due to enhanced state filling in the QWires compared to that in the QWells. Pronounced linear polarization anisotropy of the PL from the QWires verified the lateral quantum confinement of carriers. Hence, excellent optical quality of the sidewall QWire structures is demonstrated with PL peak wavelength at room temperature at 1.55 μm required for applications in fiber-based optical telecommunication systems.

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