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(In,Ga)As sidewall quantum wires on shallow-patterned InP (311)*A*

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(In,Ga)As sidewall quantum wires (QWires) are realized by chemical beam epitaxy along [01-1] mesa stripes on shallow-patterned InP (311)*A* substrates. The QWires exhibit strong lateral carrier confinement due to larger thickness and In composition compared to the adjacent quantum wells, as determined by cross-sectional scanning-tunneling microscopy and microphotoluminescence (micro-PL) spectroscopy. The PL of the (In,Ga)As QWires with InP and quaternary (Ga,In)(As,P) barriers reveals narrow linewidth, high efficiency, and large lateral carrier confinement energies of 60–70 meV. The QWires are stacked in growth direction with identical PL peak emission energy. The PL emission energy is not only controlled by the (In,Ga)As layer thickness but also by the patterned mesa height. Stacked (In,Ga)As QWires with quaternary barriers exhibit room temperature PL emission at 1.55 μm in the technologically important wavelength region for telecommunication applications. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1862763]

I. INTRODUCTION

Nanometer-scale structures on patterned substrates have been widely studied to fabricate uniform quantum wires (QWires) and quantum dots (QDots) with precisely controlled position and emission energy for optoelectronic devices. Most popular are the growth on V-groove patterned substrates[1–3] and the growth over sharp ridges.[4–6] A variety of theoretical and experimental work has been performed to improve the quality of V-groove and ridge-type QWires and QDots.[7] Both techniques rely on sharp corners or tips and, hence, relatively deep (typically several hundreds of nanometers) patterns, which are rounded in the case of V-grooves and sharpened in the case of ridges due to adatom migration from the adjacent slow-growing side facets towards the corners or tips for QWire and QDot formation. This requires reshaping of the pattern during growth of the buffer and barrier layers with considerable thickness for well-defined QWire and QDot formation and stacking in multilayers.[8,9] In addition, the sidewalls easily break up into microfacets leading to undesired size fluctuations of the QWires and QDots. Most of the studies have been performed in the (Al,Ga)As/GaAs (100) material system. The growth of V-groove and ridge-type QWires and QDots in the technologically important (In,Ga)As/InP material system for optoelectronic devices clearly turned out to be even more difficult to control.[10,11]

A complementary concept for the formation of QWires and QDots has been previously developed on shallow-patterned GaAs (311)*A* substrates. Highly uniform quasiplanar GaAs/(Al,Ga)As QWires[12,13] and QDots[14] have been realized by molecular beam epitaxy at the fast-growing sidewall of [01-1] mesa stripes in the sector towards the next (100) plane with mesa heights of several tens of nanometers.

QWire formation relies on the preferential adatom migration from the mesa top and bottom towards the sidewall, which is opposite in direction to that on V-groove or ridge-patterned (100)-oriented substrates.[15] The shallow etch depth minimizes processing induced damage for defect-free QWires and QDots. Due to the stable surface profile[16] no reshaping is required for QWire and QDot formation and stacking, allowing barrier layers of any desired thickness. Moreover, the absence of facet formation produces very smooth sidewalls and, thus, QWires and QDots with high uniformity and excellent optical properties up to room temperature.

Here we report the formation of highly uniform quasiplanar (In,Ga)As sidewall QWires by chemical beam epitaxy (CBE) on shallow [01-1] stripe-patterned InP (311)*A* substrates. The size and shape of the QWires are determined by cross-sectional scanning-tunneling microscopy (X-STM). The QWire thickness and In composition are enlarged at the mesa sidewall relative to those of the adjacent quantum well (QW), which is analyzed by microphotoluminescence (micro-PL) spectroscopy. Micro-PL reveals strong lateral carrier confinement in the QWires with InP and quaternary, lattice-matched (Ga,In)(As,P) (λ_Q=1.3 μm) barriers. The confinement energies are between 60 and 70 meV, deduced from the low-energy shift of the PL peak, which exhibits narrow linewidth and high efficiency. To increase the active volume, the QWires are stacked in growth direction with identical PL peak emission energy. The PL emission energy is controlled by the (In,Ga)As layer thickness and the height of the patterned mesa stripes. Stacked QWires with quaternary barriers exhibit room temperature emission at 1.55 μm, demonstrating device quality of the (In,Ga)As sidewall QWires on shallow-patterned InP (311)*A* substrates with potential applications for fiber-based optical telecommunication systems.

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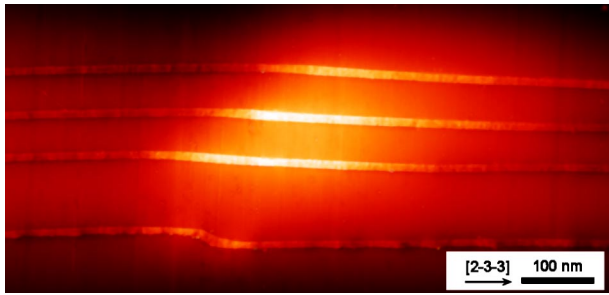
FIG. 1. (Color online) X-STM image of the sidewall QWires formed by 10 nm (In,Ga)As embedded in InP on patterned InP (311)*A* substrate, viewed along [01–1].

II. EXPERIMENT

The (In,Ga)As sidewall QWires were fabricated by CBE on shallow-patterned InP (311)*A* substrates. [01-1]-oriented mesa stripes with 4 μm width and 8 μm pitch were prepared by photolithography and wet-chemical etching in the $HCl:H_3PO_4$ (1:10) solution. The mesa height was adjusted to 20–50 nm by the etching time. The patterned substrates were cleaned in oxygen plasma and $H_3PO_4:H_2O$ (1:10) prior to overgrowth. For the CBE growth, trimethylindium, triethylgallium, AsH_3, and PH_3 were used as precursors. The AsH_3 and PH_3 gases were thermally decomposed in a high-temperature injector at 900 °C. The InP substrates were mounted on Mo blocks by In and degassed in the buffer chamber at 200 °C for 30 min before being transferred into the growth chamber. After oxide desorption, the substrate temperature was kept at 500 °C during the entire growth. The $In_{0.53}Ga_{0.47}As$ and $Ga_{0.27}In_{0.73}As_{0.59}P_{0.41}$ ($\lambda_Q=1.3$ μm) layers for QWire formation with varied thicknesses and sequences, as specified below, were lattice matched on planar InP. The structural properties of the QWires were determined by X-STM performed on the (01-1) cleavage plane in ultra-high vacuum in constant current mode. For the micro-PL measurements the samples were mounted in a He flow cryostat. The PL was excited by the 632.8 nm line of a He–Ne laser with excitation power of 10 μW through an optical microscope objective, which also served to collect the PL. The spatial resolution was 2–3 μm. The PL was dispersed by a single monochromator and detected by a cooled InGaAs charge coupled device.

III. (In,Ga)As/InP QWIRES FOR FORMATION ANALYSIS

A. Structure

Figure 1 shows the X-STM image of a stack of three sidewall QWires formed by 10 nm thick (In,Ga)As layers at a 35 nm high mesa stripe. The InP buffer layer is 100 nm, the InP separation layers between the QWires are 50 nm, and the upper InP layer is 1 μm thick. The first (In,Ga)As layer with 5 nm InP underneath marks the as-etched mesa profile in the sector towards the next (100) plane. After InP buffer layer growth, the sidewall develops a smooth curved profile, which provides the template for (In,Ga)As QWire formation. The QWires exhibit a distinct thickness enhancement close to the sidewall to a maximum of 12–13 nm with an exten-
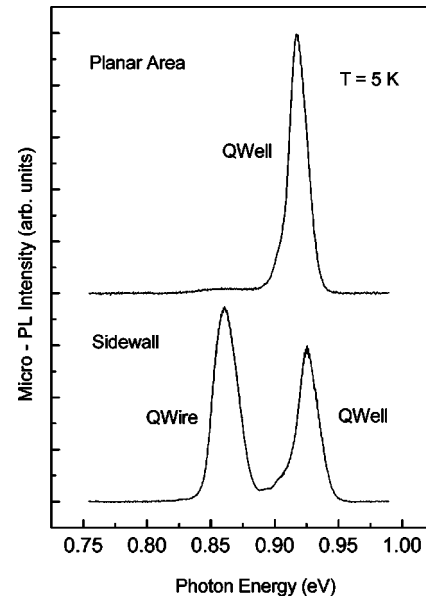

FIG. 2. Micro-PL spectra taken at 5 K from the planar area (upper curve) and from the sidewall (lower curve). The sidewall QWire is formed by 5 nm (In,Ga)As embedded in InP.

sion at the mesa bottom. This enhancement of the thickness is accompanied by In enrichment, as indicated by the height (brightness) contrast along the QWire width due to the corresponding compressive strain, leading to a proportional outward bending of the In containing structure at the cleavage plane.[17] The QWire thickness increase by a factor of 1.2–1.3 confirms the strong preferential migration of In and Ga adatoms from the planar areas towards the mesa sidewall, accompanied by In enrichment due to the larger In adatom migration length. An effective width of the tapered QWire of 200 nm is measured from the full-width at half-maximum of the thickness or In composition change along the QWire in the X-STM image. (In,Ga)As QWires are generally wider than GaAs ones,[18] again due to the larger In adatom migration length.

B. Optical properties

The optical properties of the (In,Ga)As/InP sidewall QWires are examined for a 5 nm thick (In,Ga)As layer embedded in InP. The height of the mesa stripes is 35 nm, and the thickness of the InP buffer and clad layer is 100 nm. The micro-PL spectra taken at 5 K from the planar area and the sidewall are shown in Fig. 2. The PL from the planar area exhibits a single peak centered at 0.918 eV, originating from the 5 nm thick (In,Ga)As QW. In contrast, the PL from the sidewall shows two well-separated peaks at the higher energy of 0.926 eV and at the lower energy of 0.862 eV from the QW close to the sidewall and the QWire, respectively. The PL linewidth of the QWire of 19 meV is only slightly larger than that of the QW of 15 meV. Together with the high PL efficiency and symmetric Gaussian line shape, this evidences the high uniformity and structural perfection of the QWire. The higher energy of the QW PL close to the side-
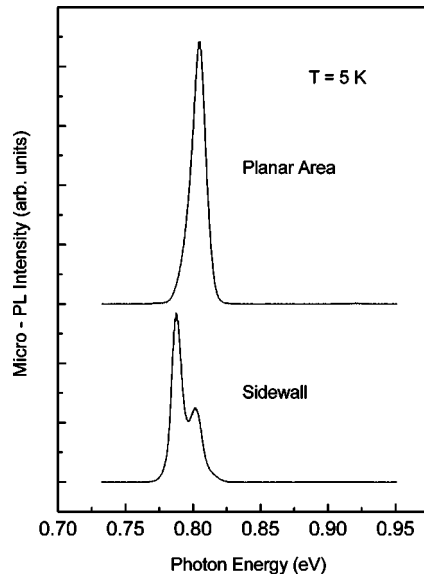
FIG. 3. Micro-PL spectra taken at 5 K from the planar area (upper curve) and from the sidewall (lower curve). The (In,Ga)As layer is 50 nm thick and embedded in InP.
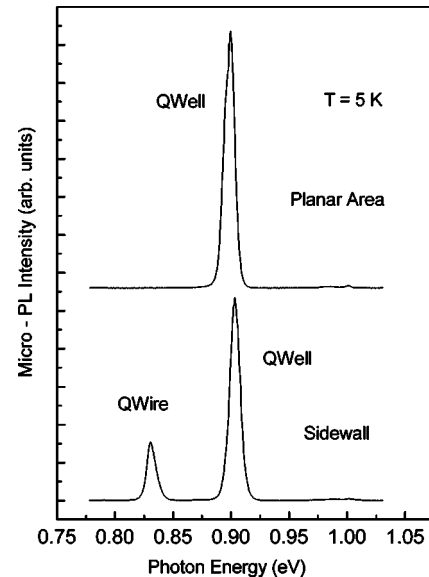
FIG. 4. Micro-PL spectra taken at 5 K from the planar area (upper curve) and from the sidewall (lower curve). The sidewall QWire is formed by 3 nm (In,Ga)As embedded in (Ga,In)(As,P).

wall confirms the preferential migration of In and Ga adatoms from the planar areas towards the sidewall, causing adjacent QW thinning.

The large energy separation between the PL from the QWire and the adjacent QW of 56 meV constitutes the lateral confinement energy of carriers in the QWire. It is comparable to that of GaAs QWires,[12] although the thickness increase, i.e., confinement energy due to the vertical quantum-size effect of the tapered (In,Ga)As QWire is smaller. The thickness increases by a factor of 2 for the GaAs QWires and by a factor of 1.2–1.3 for the present (In,Ga)As QWire. This indicates that a considerable contribution to the lateral carrier confinement energy stems from the increase of the In composition of the (In,Ga)As sidewall QWire, further reducing the optical transition energy. The opposite mesa sidewall reveals a negligible PL energy shift confirming the planarization due to preferential adatom migration away from this slow-growing shallow sidewall, which is similar to the behavior on (100)-oriented patterned substrates.

C. Thickness versus In composition increase

In order to unambiguously separate the contributions from the increase of the thickness and In composition to the lateral confinement energy, i.e., reduction of the optical transition energy of the QWire, a 50 nm thick (In,Ga)As layer is evaluated on the patterned substrate. The mesa height is 35 nm, and the InP buffer and clad layers are 50 and 100 nm thick. For this (In,Ga)As layer thickness, the influence of thickness variations on the optical transition energy is not relevant and, thus, only changes in In composition play a role. Figure 3 shows the micro-PL spectra taken at 5 K from the (In,Ga)As layer in the planar area and at the mesa sidewall. The small peak at higher energy in the spectrum from the sidewall is from the planar area side. The PL peak at the mesa sidewall, centered at 0.787 eV, exhibits a low-energy shift of 20 meV compared to that in the planar area, which is

centered at 0.807 eV, corresponding to lattice-matched $In_{0.53}Ga_{0.47}As$. This low-energy shift corresponds to a In composition at the mesa sidewall of 57%, taking the biaxial compression of the strained (In,Ga)As layer into account.

The PL peak of the (In,Ga)As layer at the sidewall is as narrow as that in the planar area, indicating a throughout homogeneous local In composition increase. Therefore, we take the same increase of the In composition for the compressively strained (In,Ga)As QWire to evaluate the lateral carrier confinement energy from the PL spectra in Fig. 2. When lateral quantum size effects are not taken into account due to the large width of the QWire, a QWire thickness increase to 6.5 nm is extracted from the difference of the QWire and QW PL peak positions, taking into account the finite InP barrier height. This is 1.3 times the thickness of the 5 nm (In,Ga)As QW, which is in agreement with the thickness increase of the QWire determined from X-STM. Hence, the lateral carrier confinement energy of the sidewall (In,Ga)As QWires on shallow-patterned InP (311)A substrates is governed by a 4% enhancement of the In composition and a thickness increase by a factor of 1.2–1.3 due to preferential In and Ga migration from the mesa top and bottom towards the fast-growing sidewall, which is favored for In adatoms due to the larger surface migration length.

IV. (In,Ga)As/(Ga,In)(As,P) QWIRES FOR PHOTONIC DEVICES

A. Optical properties

The InP barrier layers of the sidewall QWires are replaced by lattice-matched quaternary (Ga,In)(As,P) with λ_Q = 1.3 μm, which is widely employed as waveguide core material in InP-based photonic devices. Figure 4 shows the micro-PL spectra taken at 5 K from the sidewall QWire formed by 3 nm (In,Ga)As with 120 nm lower and upper (Ga,In)(As,P) barriers. The mesa height is 50 nm and the InP buffer layer thickness is 20 nm. The QW layer thickness is
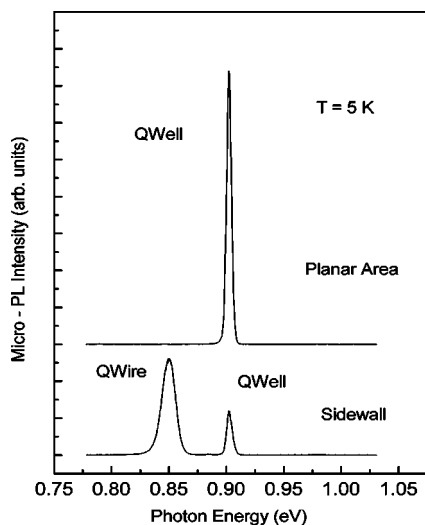
FIG. 5. Micro-PL spectra taken at 5 K from the planar area (upper curve) and from the sidewall (lower curve). The threefold stacked sidewall QWires are formed by 3 nm (In,Ga)As embedded in (Ga,In)(As,P).

reduced from 5 to 3 nm to shift the PL emission in the same energy region for the lower (Ga,In)(As,P) energy barrier height. The upper PL spectrum with peak emission at 0.899 eV is taken from the planar area, and the lower one from the sidewall with a peak centered at 0.903 eV from the adjacent QW and a peak centered at 0.831 eV originating from the QWire. The slight high-energy shift of the QW PL close to the sidewall and the large peak separation of the QWire and QW emission reveal an unchanged formation mechanism of the (In,Ga)As sidewall QWire on (Ga,In)(As,P) with an even larger lateral carrier confinement energy of 68 meV. This mainly results from the thinner QW layer, confirming that the QWire thickness enhancement and In enrichment are maintained. The linewidth of the sidewall QWire of 9 meV is reduced, as is that of the QW in the planar area of 9 meV, again due to the reduced quaternary energy barrier height together with the high structural uniformity of the QWire. In addition, some In enrichment in the quaternary (Ga,In)(As,P) layers above the sidewall, though not clearly observed in PL, cannot be excluded to further reduce the energy barrier height, contributing to the QWire PL low-energy shift and linewidth reduction.

B. Stacking

To increase the active volume, the QWires embedded in quaternary (Ga,In)(As,P) barriers are stacked in the growth direction. The layer structure comprises a 20 nm InP plus 20 nm (Ga,In)(As,P) buffer followed by three 3 nm thick (In,Ga)As layers separated and overgrown by 50 nm (Ga,In)(As,P). The mesa height is 35 nm. The micro-PL spectra taken at 5 K from the planar area and the sidewall are shown in Fig. 5. The PL spectra are very similar compared to those of the single sidewall QWire in Fig. 4. The linewidth of the PL spectrum of the QWires of 12 meV is only slightly larger with symmetric Gaussian line shape, indicating almost identical peak emission energy of all three stacked QWires. This is attributed to the stable surface profile, evolving during the thin buffer layer growth, which allows the vertical

stacking of QWires with identical shape and In composition. The different appearance of the stacked QWires in the X-STM image in Fig. 1 is due to a superimposed varying background height contrast slope.

C. Emission energy control

Tuning of the emission energy of the QWires is not only possible by the thickness of the (In,Ga)As layer but also by the height of the mesa stripes, which is adjusted by the etching process. Figure 6 depicts the peak emission energy at 5 K of the QWires as a function of the mesa height. The (In,Ga)As layer thickness is 3 nm, and the thickness of the lower and upper (Ga,In)(As,P) barriers on the 20 nm InP buffer is 120 nm. With increasing mesa height, the emission energy of the sidewall QWires continuously shifts to lower energies, starting to saturate above a mesa height of 50 nm. Hence, the thickness and In composition of the QWires are enhanced when the height of the mesa stripe is increased in the several tens of nanometers range. This is attributed to a steeper surface profile after buffer layer growth since the total sidewall height remains unchanged during overgrowth. For too high mesa height, the growth selectivity saturates and decreases when the accumulation of In and Ga adatoms at the sidewall becomes limited by the migration length. The dependence of the emission energy on the mesa height, furthermore, explains the small difference in PL peak position of the single and triple QWires in Figs. 4 and 5.

D. 1.55 μm emission at room temperature

Figure 7 shows the PL spectra taken at room temperature of the threefold stacked sidewall QWire structure of Fig. 5. The upper PL spectrum of the QWs in the planar area exhibits a peak emission at 0.840 eV due to the electron–heavy hole transition and a shoulder at 0.890 eV originating from the electron–light hole transition. The features in the spectrum around 0.9 eV are due to water absorption and the peak at 0.94 eV stems from the quaternary (Ga,In)(As,P) barriers. The peak intensity drops by a factor of 1000 between 5 K and room temperature due to thermally activated carrier escape. At the sidewall, the PL spectrum reveals a clear shoulder at lower energy due to the emission from the QWires. Using a Gaussian fit, a peak energy of 0.80 eV is determined, corresponding to the emission wavelength of 1.55 μm. Hence, the large lateral carrier confinement energy, excellent uniformity, increase of the active volume by stacking, and
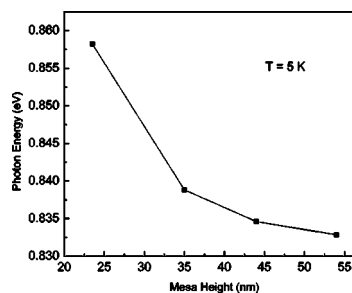

FIG. 6. Dependence of the emission energy at 5 K of the sidewall QWires on the height of the patterned mesa stripes. The QWires are formed by 3 nm (In,Ga)As embedded in (Ga,In)(As,P).
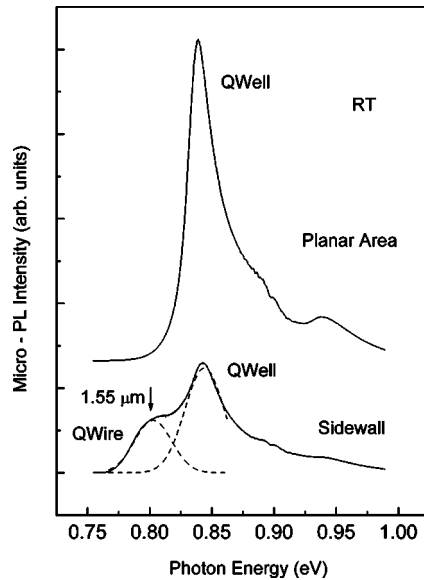
FIG. 7. Micro-PL spectra taken at room temperature from the planar area (upper curve) and from the sidewall (lower curve). The threefold stacked sidewall QWires are formed by 3 nm (In,Ga)As embedded in (Ga,In)(As,P). The dashed lines in the lower spectrum are Gaussian fits.

emission energy control by the mesa height demonstrate device quality of the (In,Ga)As sidewall QWires in (Ga,In)(As,P) for photonic devices operating in the 1.55 μm wavelength region at room temperature.

V. CONCLUSIONS

We have fabricated quasiplanar (In,Ga)As sidewall quantum wires (QWires) along [01-1] mesa stripes on shallow-patterned InP (311)A substrates by CBE. The structural analysis by X-STM revealed thickness increase and In enhancement close to the mesa sidewall, which has been precisely evaluated by micro-PL spectroscopy. The QWires embedded in InP and lattice-matched quaternary (Ga,In)(As,P) barrier layers revealed narrow PL linewidths, high PL efficiency, and large lateral carrier confinement energies. The QWires have been stacked in growth direction with identical PL peak energies. The emission energy of the QWires has been controlled by the (In,Ga)As layer thickness and the height of the patterned mesa stripes. Room temperature PL emission centered at 1.55 μm has been demonstrated for stacked QWires embedded in (Ga,In)(As,P) barriers. Hence, the potential of (In,Ga)As sidewall QWires on shallow-patterned InP (311)A substrates for photonic devices operating in the 1.55 μm telecommunication wavelength region is established.

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