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Enhancement of optical nonlinearity in strained (InGa)As sidewall quantum wires on patterned GaAs (311)A substrates

Richard Nötzel,[a] Manfred Ramsteiner, Zhichuan Niu, Hans-Peter Schönherr, Lutz Däweritz, and Klaus H. Ploog
Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

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Strong enhancement of the optical nonlinearity occurs in strained (InGa)As sidewall quantum wires grown on patterned GaAs (311)A substrates by molecular beam epitaxy. The wires are formed on the fast growing sidewall of mesa stripes along [01-1] and have a smooth, convex-curved surface profile. The blue shift of the photoluminescence peak energy of the wire in dependence on the excitation power is one order of magnitude larger compared to that of the surrounding well. This enhanced optical nonlinearity is assigned to additional lateral optical band gap modulation due to internal piezoelectric fields effective in the present quantum-wire structure. © *1997 American Institute of Physics.* [S0003-6951(97)02512-6]

We have recently fabricated lateral quantum wires utilizing a new type in the selectivity of growth found on patterned GaAs (311)A substrates.[1] During molecular beam epitaxy (MBE) of (AlGa)As over mesa stripes oriented along the [01-1] direction, a fast growing sidewall evolves on one side in the sector towards the next (100) plane. Cathodoluminescence (CL) and microphotoluminescence (μ-PL) measurements have confirmed the preferential migration of Ga adatoms from the mesa top and mesa bottom towards the sidewall to develop a smooth, convex-curved surface profile without faceting. Lateral quantum wires have been formed along 10–20 nm high steps.[2] The wires, having a height of about twice the thickness of the neighboring well and a width of several 10 nm exhibit a smooth surface morphology and high homogeneity along the sidewall. The PL spectra are characterized by narrow PL linewidth and high PL efficiency between 5 K and room temperature. The μ-PL linescans have revealed strong lateral localization and confinement of the photogenerated carriers in the wires up to room temperature. The two-dimensional (2D) quantum confinement of excitons has been demonstrated by the changeover from 2D to magnetic confinement with increasing magnetic field. The wires could be stacked in growth direction allowing the fabrication of three-dimensional arrays.[3]

In the present study, we report on the enhancement of the optical nonlinearity of strained (InGa)As quantum wires due to internal piezoelectric fields. Owing to the piezoelectricity of GaAs, an electric polarization is induced in strained heterostructures grown along directions different from [100].[4] The vector of the polarization on [hkl] oriented substrates points towards the [1 h/l h/k] direction.[5] Depending on the geometrical situation, the polarization induces electric charge at the interfaces of the strained layer, thus creating an internal electric field. Due to the corresponding linear change in potential energy across the structure, the conduction and valence bands are tilted to effectively reduce the optical band gap resulting in a red shift of the absorption and PL. Optical modulation is now obtained when the interface charges are screened by the photogenerated carriers, thus blue shifting the PL with excitation power. In 2D quantum wells, however, only the vertical component $P_\perp$ of the polarization is effective to electrically charge the interfaces to built up an electric field in growth direction. On the other hand, in quantum wires with directions perpendicular to [1 h/l h/k], full use of the polarization can be made.[6] In this case, also the in-plane component of the polarization $P_\parallel$ induces interface charges at the borders of the wire to produce a lateral electric field in addition to the vertical one.

This situation is matched for the present sidewall quantum wires along [01-1] on patterned GaAs (311)A substrates where, in addition, $P_\parallel$ has a local maximum.[5] A schematic of the structure and cross-sectional scanning-electron microscopy image (SEM) are shown in Figs. 1(a) and 1(b) with the vector of the electric polarization **P** in the [133] direction [Fig. 1(c)]. When considering the shear strain on GaAs (311)A substrates, that becomes increasingly important for higher In composition, the vector of the polarization is even more rotated into the plane.[7] For an In composition of 0.2, the magnitude of the polarization amounts to 1×10^{-3} C/cm^2 corresponding to a vertical electric field $E_\perp$ of 5×10^4 V/cm and an in-plane electric field $E_\parallel$ of 6×10^4 V/cm ($E_{\perp,\parallel}=P_{\perp,\parallel}/\epsilon_0\epsilon_r$).[5] ϵ_r and ϵ_0 are the dielectric constant and the vacuum permeability, respectively. The corresponding change in potential energy, i.e., reduction of the optical band gap in vertical or lateral direction is proportional to the product of $E_\perp$ with the height or $E_\parallel$ with the width of the wire. Therefore, for quantum wires having a width much larger than the height, the optical nonlinearity will originate mainly from the in-plane electric field. In that case, the total charge generating the in-plane field is smaller by a factor of height/width compared to that generating the vertical field and, hence, strong optical modulation occurs at much lower excitation power.[6]

The 10-μm-wide and 20-nm-deep mesa stripes along [01-1] were prepared on GaAs (311)A substrates by optical lithography and wet chemical etching using the $H_2SO_4:H_2O_2:H_2O$ (1:8:40) preferential etching solution. After cleaning the substrates, the native oxide was removed at 580 °C in the MBE growth chamber. A 50-nm-thick GaAs buffer layer and a 50 nm thick lower $Al_{0.5}Ga_{0.5}As$ barrier layer were grown at 620 °C before the substrate was cooled down to 520 °C for growing a 3-nm-thick $In_{0.2}Ga_{0.8}As$ layer.

[a]Electronic mail: notzel@pdi.wias-berlin.de

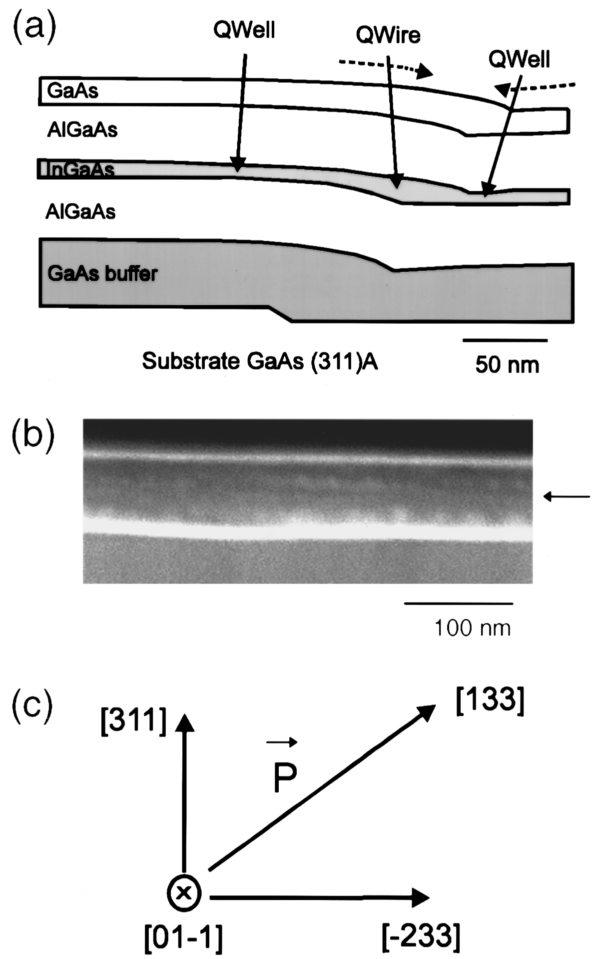

FIG. 1. (a) Schematic of the strained (InGa)As sidewall quantum wire on patterned GaAs (311)A substrates and (b) cross-sectional SEM image of the (InGa)As quantum wire connected with the 6-nm-thick $In_{0.2}Ga_{0.8}As$ quantum well (see arrow). In (c), the vector of the piezoelectric polarization in the strained wire is indicated.

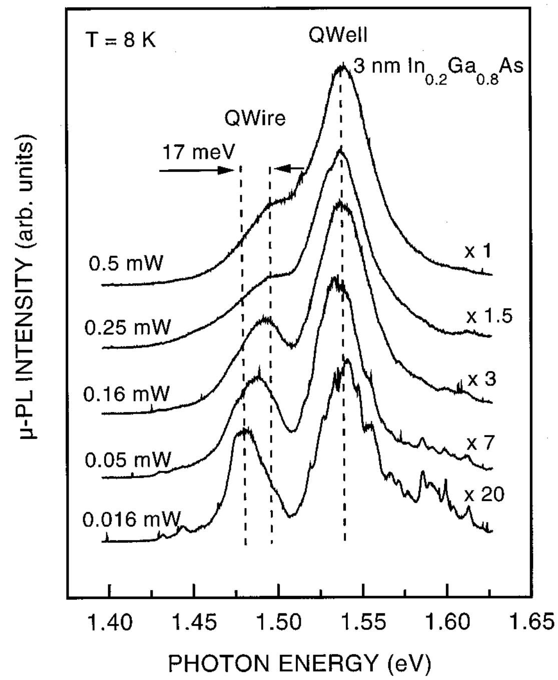

FIG. 2. μ-PL spectra taken at 8 K excited on the (InGa)As wire region connected with the 3-nm-thick $In_{0.2}Ga_{0.8}As$ quantum well for different excitation power.

Then, the substrate was again heated up to 620 °C and the upper, 50-nm-thick $Al_{0.5}Ga_{0.5}As$ barrier layer and a 10-nm-thick GaAs cap were grown. For comparison, similar structures have been grown with 6-nm-thick $In_{0.1}Ga_{0.9}As$ and $In_{0.2}Ga_{0.8}As$ layers. The growth rates for (InGa)As and (AlGa)As were 0.3 and 0.6 μm/h. The group-V-to-III-flux ratio was about 5. The layers were characterized by SEM, atomic force microscopy (AFM), and μ-PL. The μ-PL studies were carried out at 8 K using a confocal imaging system. The spot diameter on the sample surface was about 2 μm. The PL was excited with an Ar^+ laser with excitation power ranging from 5×10^{-3} to 1 mW.

The SEM image in Fig. 1 reveals the presence of the thicker wirelike regions along the sidewall for the strained (InGa)As structure with a width of about 100 nm. AFM has confirmed the smooth morphology of the convex curved sample surface. In Fig. 2, the μ-PL spectra excited on the (InGa)As wire region connected with the 3-nm-thick $In_{0.2}Ga_{0.8}As$ quantum well are shown in dependence on the excitation power. The PL line at lower energy corresponds to the emission from the (thicker) wire and that at higher energy to that from the adjacent well at the mesa top and bottom, in analogy to the unstrained GaAs/(AlGa)As system.[2] The linewidth of the PL from the wire is not larger compared to that from the well. The reproducible fine structure in the PL spectra at low excitation power is attributed to the emission of localized excitons.[8,9] Most important, the PL from the wire shows a strong blue shift of up to 17 meV for an increase of the excitation power by only one order of magnitude whereas the PL energy of the well remains almost constant with a blue shift of at most 1–2 meV at high excitation power. The blue shift of the PL peak energy positions of the wire and the well as a function of the excitation power is plotted in Fig. 3 for clarity.

In agreement with the strain state, the blue shift of the PL from the wire, being 17 meV for the In composition of 0.2 is reduced to 7 meV for the In composition of 0.1 in different samples. The unstrained GaAs/(AlGa)As structures exhibit no blue shift thus excluding the population of higher subbands in the wires. Therefore, the enhanced blue shift of the PL from the strained wire compared to that from the adjacent well in Fig. 2 can arise from the larger vertical and lateral optical band gap modulation due to its increased thickness together with the additional in-plane electric field. However, the PL of the 6-nm-thick reference $In_{0.2}Ga_{0.8}As$ (311)A quantum well again shows a blue shift of only 1–2 meV. Therefore, the blue shift of the PL from the wire is mainly attributed to the lateral optical band gap modulation effective in the present structure: The enhancement of the blue shift is proportional to the ratio of width to height and the relevant in-plane charge density is reduced by the same factor to the mid 10^{10} cm^{-2} range, which is easily accessible by photogenerated carriers. Hence, strong optical modulation in the strained quantum wires is achieved for medium In composition where high-quality layers with large critical thickness are obtained.

A quantitative analysis, however, will require full

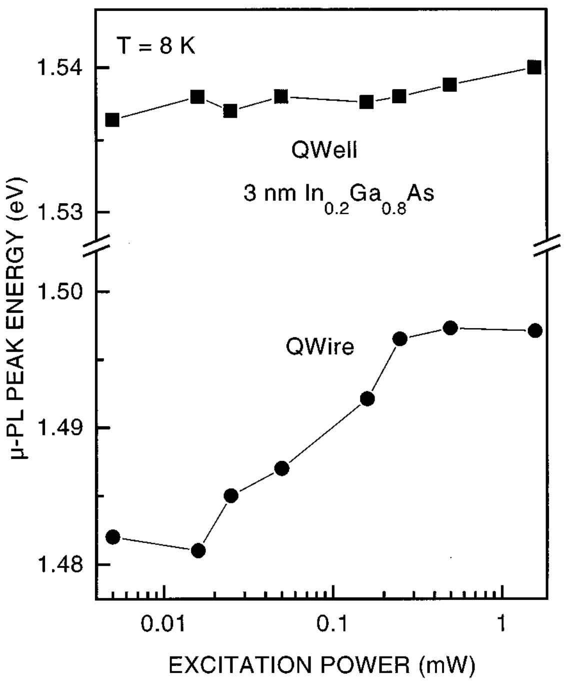

FIG. 3. μ-PL peak energy positions at 8 K of the (InGa)As quantum wire and quantum well in dependence on the excitation power. The thickness of the quantum well is 3 nm with an In composition of 0.2.

knowledge of the In composition and distribution inside the wire. For instance, the blue shift of the PL from the wire in Fig. 2 towards that from the 3 nm $In_{0.2}Ga_{0.8}As$ well at high excitation power already results in a smaller confinement energy in the screened wire (~40 meV) compared to that of unstrained GaAs/(AlGa)As wires formed from quantum-well layers with similar thickness (80–100 meV).[2,3] Moreover, the PL peak energy of the (screened) wire is about 120 meV larger than that of the 6-nm-thick reference $In_{0.2}Ga_{0.8}As$ quantum well. This suggests a smaller In composition in the wire relative to that in the well, and/or a reduced height compared to the unstrained wires, that is also found for ridge-type structures on patterned GaAs (100) substrates.[10] Yet, in view of applications, stacking the strained quantum wires in dense arrays will allow the fabrication of optical modulators with high modulation depth operating at low incident power.

In conclusion, we have fabricated strained (InGa)As quantum wires on patterned GaAs (311)A substrates by molecular beam epitaxy. The wires are formed on the fast growing sidewall of mesa stripes along [01-1] and exhibit a smooth, convex-curved surface profile. The microphotoluminescence spectra of the wires undergo a strong blue shift with excitation power, one order of magnitude larger compared to that of the surrounding wells. This enhanced optical nonlinearity is attributed to additional lateral optical band gap modulation due to internal piezoelectric fields, that will allow the fabrication of efficient strained quantum wire optical modulators.

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