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Three-dimensional arrays of vertically stacked sidewall quantum wires are fabricated by molecular beam epitaxy on GaAs (311)*A* substrates patterned with 500-nm-pitch gratings. The cathodoluminescence spectra at low temperature are dominated by the emission from the quantum wires with narrow linewidth accompanied by a very weak emission from the connecting thin quantum wells due to localization of excitons at random interface fluctuations. When the carriers in the quantum well become delocalized at elevated temperature, only the strong emission from the quantum-wire array is observed revealing perfect carrier capture into the quantum wires without detectable thermal repopulation of the quantum well up to room temperature. Thus, unpreceded device quality of this quantum-wire structure is demonstrated. © *1998 American Institute of Physics.* [S0003-6951(98)03016-2]

In sub-μm-pitch quantum-wire or -dot arrays the lateral periodicity is smaller than the diffusion length of free carriers. This has pronounced impact on their electronic properties, in particular, the optical emission characteristics, which become dominated by transitions in the quantum wires or dots due to the efficient carrier capture into the active region, crucial for the operation of devices. In addition, for practical applications in devices, it is desirable to further increase the active volume by vertically stacking the nanostructures in dense, three-dimensional arrays. Self-organized growth and the growth on substrates patterned with V grooves can in principle fulfill these prerequisites by producing quantum-wire and -dot arrays free of defects.[1] However, in most self-organizing processes, the control of the position and uniformity of the nanostructures is not sufficient, and V-groove quantum wires exhibit increased irregularities when fabricated on sub-μm gratings with reduced growth selectivity, i.e., lateral confinement energy,[2] although low-threshold current GaAs quantum-wire lasers indicating distributed feedback operation were already reported.[3,4]

We have successfully fabricated vertically stacked arrays of sidewall quantum wires on GaAs (311)*A* substrates patterned with sub-μm-pitch gratings, which exhibit excellent optical properties. The wires are formed in a new growth mechanism recently found in molecular beam epitaxy (MBE) of (AlGa)As on patterned GaAs (311)*A* substrates due to preferential migration of Ga adatoms from the mesa top and bottom towards one of the sidewalls of mesa stripes oriented along [01-1].[5] For mesa heights in the quantum-size regime, this results in quasiplanar lateral GaAs/(AlGa)As quantum wires with several 10 nm width, which are bound by a very smooth, convex-curved surface profile. Their maximum height is about twice as large as that of the quantum wells in the flat parts connecting the wires. Single quantum wires have shown narrow photoluminescence (PL) linewidths, high PL efficiency, and strong lateral carrier confinement up to room temperature.[6] The one-dimensional quantum confinement of excitons was independently confirmed from the diamagnetic shift in magneto-PL[7] and from the observation of one-dimensional subbands in near-field PL excitation spectroscopy.[8]

On sub-μm-pitch gratings the selectivity of growth at the fast growing sidewall is even enhanced compared to that on several μm-wide mesa stripes resulting in an increased thickness and, consequently, a larger lateral confinement energy of carriers in the wires. The growth on these narrow gratings does neither affect the uniformity of the wires nor the possibility to vertically stack them in the growth direction.[7] The dense array exhibits strong cathodoluminescence (CL) emission with narrow linewidth comparable to state-of-the-art quantum wells on planar substrates. The CL spectra are dominated by the emission of the quantum-wire array with a weak emission from the quantum well at low temperature due to carrier localization at random interface fluctuations. For increasing temperature, only the CL from the quantum-wire array is detectable, thus indicating perfect carrier transfer with high CL efficiency up to room temperature without thermal repopulation of the quantum well.

The GaAs (311)*A* substrates were patterned with 500-nm-pitch periodic gratings using holographic lithography and dry etching to a depth of 15 nm. After cleaning the samples in concentrated H_2SO_4, the native oxide was removed in the preparation chamber by atomic hydrogen irra-

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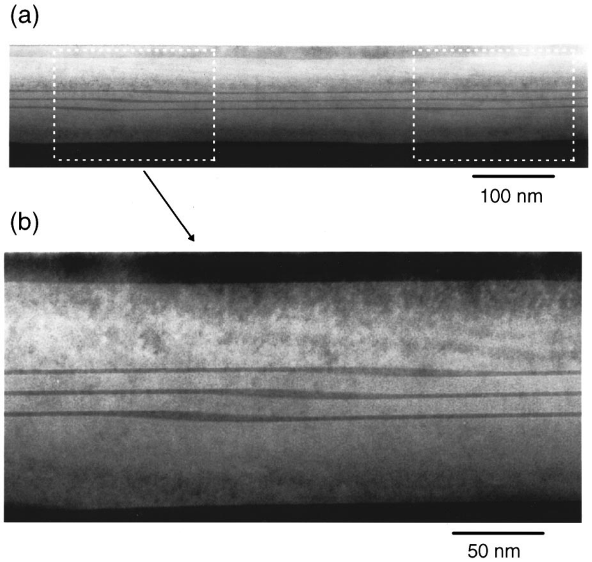

FIG. 1. (a) Cross-sectional TEM image viewed along [01-1] of the 500-nm-pitch array of vertically stacked sidewall quantum wires on patterned GaAs (311)*A* substrates. In (b) the scale is enlarged.

diation before loading them into the MBE growth chamber. The layer sequence comprised a 50-nm-thick GaAs buffer layer and a 50-nm-thick $Al_{05}Ga_{0.5}As$ lower barrier layer followed by a stack of three 3-nm-thick GaAs quantum-well layers each separated by 10-nm-thick $Al_{0.5}Ga_{0.5}As$ barrier layers, and a 50-nm-thick upper $Al_{0.5}Ga_{0.5}As$ barrier layer capped with a 20-nm-thick GaAs layer.[7] A reference quantum well was grown side by side on a planar GaAs (311)*A* substrate. After growth the samples were investigated by cross-sectional transmission electron microscopy (TEM), and spectrally as well as spatially resolved CL measurements between 5 K and room temperature.

Figure 1(a) shows the cross-sectional TEM overview of two stacks of quantum wires separated laterally by 500 nm. The wires appear as the thicker dark regions connected with the thinner quantum wells in between, which are embedded in the (AlGa)As layers with lighter contrast. During the growth of the GaAs buffer layer, the fast growing sidewall develops the well-defined convex-curved surface profile, while the opposite slow growing sidewall with concave curvature smears out, thus providing a uniform template for the quantum well. The surface profile is maintained during the growth of the (AlGa)As barrier layers. In the TEM image in Fig. 1(b) with higher resolution, the stack of three wires with virtually the same shape and size is clearly seen indicating a self-limiting lateral growth mechanism.[7] The thickest region in the center of the wires is more than twice as thick as the quantum well thickness with an effective width of less than 50 nm. The selectivity of growth on the sub-μm-pitch grating is higher compared to that at wide mesa stripes, as will be seen also from the CL measurements. This behavior is attributed to the small periodicity of the grating allowing Ga adatoms to migrate directly from the slow growing to the fast growing sidewall in order to increase the thickness of the quantum wire at cost of the quantum-well thickness.

Figure 2 shows the laterally averaged CL spectra recorded between 5 K and room temperature of the quantum-wire array (solid lines) together with the spectrum of the

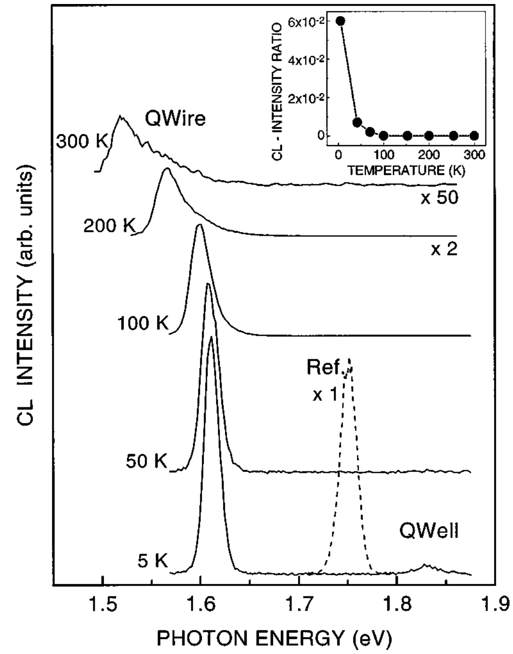

FIG. 2. CL spectra of the sidewall quantum-wire array on patterned GaAs (311)*A* substrates between 5 K and room temperature (solid lines) and of the reference quantum-well sample on the planar substrate (dashed line). The inset shows the ratio of the CL intensity from the connecting quantum wells to that of the sidewall quantum wires as a function of the temperature.

reference quantum well (dashed line). The area of excitation is $6\times 4\ \ \mu m^2$. The spectra at 5 K are dominated by the emission from the quantum wires at 1.611 eV revealing effective carrier capture from the adjacent quantum well. The remaining weak emission from the quantum well at 1.831 eV is attributed to localization of carriers therein due to random interface fluctuations as will be discussed later. The narrow linewidth of the CL of the quantum-wire array, comparable to that of the reference quantum-well CL centered at 1.752 eV, reveals its high structural perfection and uniformity in size and shape of the three-dimensionally stacked wires. The quantum efficiency of the wire array is comparable to that of the reference quantum well for the same excitation conditions, thus excluding nonradiative losses during the transfer of the free carriers at low temperature. The redshift of the quantum wire and, in particular, the blueshift of the quantum-well CL line with respect to that of the reference quantum well is much larger compared to that of single quantum wires at wide mesa stripes with similar structural parameters.[7] This confirms the higher growth selectivity resulting in a lateral confinement energy, i.e., energy separation of the CL lines of the quantum wires and adjacent quantum well as high as 220 meV for the present structure giving energy separations of the subbands for electrons in the range of $k_B T$ at room temperature (25 meV).[2,3]

The quantum-wire array exhibits strong CL emission up to room temperature with an overall drop in intensity of only one to two orders of magnitude due to nonradiative recombination and/or thermal reemission of carriers into the (AlGa)As barrier layers,[9] which underlines its high structural perfection. Moreover, with increasing temperature, the emission from the quantum well is strongly reduced relative to that of the quantum-wire array. This reveals thermally activated delocalization of carriers in the quantum well allowing

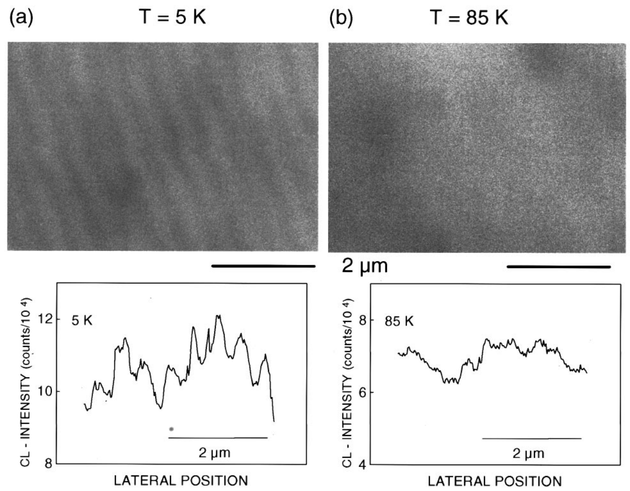

FIG. 3. Lateral CL-intensity distribution detected at the quantum wire peak position (a) at 5 K (1.611 eV) and (b) at 85 K (1.604 eV) together with the corresponding CL-intensity linescans across the wires.

perfect transfer into the quantum wires before radiative recombination can take place. This behavior is shown in the inset of Fig. 2, where the CL-intensity ratio of the quantum-well to -wire emission $I_{\mathrm{QWell}}/I_{\mathrm{QWire}}$ is plotted as a function of the temperature. The ratio drops by one order of magnitude between 5 and 50 K and, within the sensitivity of the system (the signal-to-noise ratio is at least 10^3), remains zero up to room temperature. This, in addition to the very efficient carrier capture, shows the absence of thermal repopulation of the quantum well up to room temperature due to the high confinement energy of 220 meV, which was not achieved for the single quantum wires with 62 meV lateral confinement energy.[8] The measurable CL-intensity ratio of 0.06 of the quantum-well-to-wire emission at 5 K provides an upper limit for the transfer time of the carriers of several ps by considering it to be equal to the ratio of the trapping time into the wires and the radiative recombination time in the quantum well, the latter being several 100 ps, which has been confirmed by time-resolved spectroscopy. This value is in agreement with trapping times determined for V-groove quantum wires.[2,10]

Carrier localization in the quantum well at low temperature and delocalization at higher temperature is directly evidenced in the lateral CL-intensity distributions at 5 and 85 K detected at the peak position of the CL of the quantum wires, depicted in Fig. 3 together with the corresponding CL intensity linescans perpendicular to the wires. The (monochromatic) CL images show intensity fluctuations similar to those commonly observed for thin quantum wells due to random fluctuations of the layer thickness, i.e., CL-peak position giving rise to localization of free carriers at low temperature.[11,12] More important, at 5 K a shallow intensity modulation with 500 nm periodicity following the wire array is observed. The modulation depth is about 6% of the total signal, which coincides exactly with the intensity ratio of the well to wire emission meaning that all the missing carriers in the wires remain and decay in the well without nonradiative losses. The CL-intensity linescans of the quantum-well emission (not shown here) show similar periodic modulations with opposite phase compared to those of the CL of the quantum wires. Here, the localization of the carriers at low temperature is helpful to directly visualize the spatial uniformity of the quantum wire array. At 85 K [Fig. 3(b)] the periodic CL-intensity modulation of the quantum-wire emission disappears, which confirms the delocalization of the carriers in the quantum well. The CL intensity of the quantum wires becomes independent on the location of carrier excitation due to complete transfer of the radiatively decaying carriers into the quantum wires.

In conclusion, we have fabricated very uniform arrays of vertically stacked sidewall quantum wires on sub-μm-pitch gratings on patterned GaAs (311)A substrates. Spectrally and spatially resolved CL measurements are dominated by the emission from the quantum wires with a narrow linewidth accompanied by a very weak emission from the connecting quantum well at low temperature, which is attributed to localization of excitons at random interface fluctuations. At elevated temperature, only the emission from the quantum-wire array remains due to delocalization of the carriers in the quantum wells resulting in perfect carrier trapping into the quantum wires. Strong emission from the quantum-wire array is observed up to room temperature without detectable thermal repopulation of the quantum well, which opens the door for using this quantum-wire structure as active medium in various semiconductor devices.

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