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(110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells for optimized T-shaped quantum wires

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High control of (110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells is very important for the growth of optimized T-shaped GaAs/AlGaAs quantum wires. We investigate theoretically and experimentally 20–200 Å wide (110) oriented GaAs quantum wells grown on (110) oriented substrates and cleaved edges. Photoluminescence transition energies are found to be in good agreement with theory for all well widths. The mean well width is controllable to 1 monolayer accuracy and an effective well width fluctuation of 3.7 Å is derived from the photoluminescence linewidths. The growth rate calibration of the aluminum content of the barrier material agrees within 1% with an estimate from the bound exciton emission of (110) $Al_{0.3}Ga_{0.7}As$ epilayers. © *1996 American Institute of Physics.* [S0003-6951(96)00632-8]

There is currently a strong interest in low-dimensional semiconductor nanostructures. By molecular beam epitaxy (MBE) cleaved edge overgrowth,[1] GaAs quantum wires are formed at the T-shaped intersections between multiple quantum wells (MQWs) grown on (001) oriented GaAs substrates, and a (110) oriented quantum well (QW) overgrown on the cleaved edge (T-QWRs).[2–6] However, the one-dimensional confinement potentials are below 28 meV in most cases[2–6] as measured by low-temperature photoluminescence (PL). Recently, a confinement of 54 meV was realized in an optimized design of the QW widths and the aluminum contents incorporated in the structure.[7]

In the optimized design, the (001) and (110) QWs have equal ground state energies for the heavy-hole excitons. But because of the valence band anisotropy, equal energies of GaAs QWs are not obtained by equal (001) and (110) QW widths as it has previously been assumed.[4,6] To match the energies, the transition energy of the (001) MQW is measured after growth and the (110) QW is then designed and overgrown, so the transition energies of the wells coincide. This procedure is especially important for (001) MQWs with aluminum in the wells, grown by a digital alloy technique with rapid shutter operations of the aluminum cell, giving rise to deviations from the expected transition energies.[2,7] For the overgrowth, high control of (110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ QWs is necessary. However, the (110) growth is complicated by the lower quality of the MBE growth on (110) oriented substrates.[8]

In this letter, we investigate the (110) oriented GaAs/$Al_{0.3}Ga_{0.7}As$ QWs. We show that the QW ground state energy, as a function of well width, is in good agreement with an effective mass theory using the heavy-hole effective mass in the (110) direction. These results indicate that the (110) growth rates, and hence the QW width and the aluminum composition of the barrier, can be well controlled by the MBE growth. To test the composition of the barrier, the bound exciton (BE) position in two bulk (110) $Al_{0.3}Ga_{0.7}As$ samples was measured. Here, we find an excellent agreement with the intended calibration of the aluminum content. We also illustrate the properties of the (110) oriented GaAs QW by the spectrum of a 70 Å symmetric T-QWR.

The samples were grown in a Varian Modular Gen II, 3-in. MBE machine. An electrical and optical characterization of the As_2-grown (110) GaAs/AlGaAs has been reported previously.[9] The growth rate was calibrated by reflection high energy electron diffraction (RHEED) on a (001) GaAs wafer. A high V/III beam equivalent pressure ratio of 20–30 was used together with a low substrate temperature of about 460 °C in most cases. A series of MQW samples was grown on (110) substrates with a 5000 Å GaAs buffer layer followed by 20 periods of 200 Å $Al_{0.3}Ga_{0.7}As$ barriers and GaAs QWs of thicknesses varying from 20 to 200 Å.

PL measurements were performed at 4 K with the samples mounted in a continuous-flow cryostat using HeNe laser excitation (632.8 nm, 4 W/cm^2), except for the PL of the two (110) $Al_{0.3}Ga_{0.7}As$ samples where an argon ion laser excitation (488 nm, 0.1 W/cm^2) was used. The PL was dispersed in a 0.66 m focal length spectrometer, detected by a photomultiplier tube with a cooled GaAs photocathode, and recorded using either lock-in or photon counting techniques.

In Fig. 1, the experimental (110) QW transition energies are plotted together with the calculated values. The inset shows calculated redshifts from the (001) transition energies and typical experimental redshifts from the transition energies of (001) structures grown under optimized (001) growth conditions.

The calculations in Fig. 1 are performed by solving the transcendental equation for energy eigenvalues for the even ground states.[10] We use $\Delta E_v = 0.15$ eV and $\Delta E_c = 0.24$ eV for the valence band and conduction band offsets

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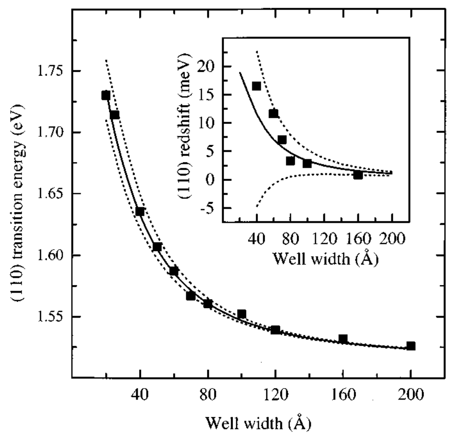

FIG. 1. Calculated (curves) and experimental values (symbols) for the (110) QW transition energies at 4 K and for the (110) QW redshift. Dashed curves are calculations assuming an error of ±4 Å in the (110) QW width. The data for the 70 Å well width are from a PL spectrum of a T-QWR (see Fig. 4).

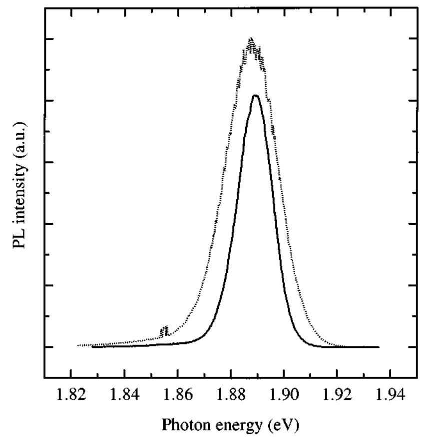

FIG. 3. BE emission at 4 K from two 5000 Å thick (110) $Al_{0.3}Ga_{0.7}As$ epilayers grown at substrate temperature of 460 °C (solid curve) and 430 °C (dotted curve), respectively.

at the GaAs/$Al_{0.3}Ga_{0.7}As$ interface and the effective electron and hole masses $m_e = 0.067m_0$, $m_{hh}(001) = 0.33m_0$, and $m_{hh}(110) = 0.60m_0$.[11–14] Exciton binding energies, as a function of well width, are found by an interpolation between experimental values of Koteles *et al.*[15] The dashed curves are included to illustrate the effects of an assumed error of ±4 Å (two monolayers) in the nominal (110) QW width.

The (110) transition energies in Fig. 1 are in very good agreement with the calculation for the nominal (110) QW width. The calculated redshifts in Fig. 1, for the nominal (110) and (001) QW widths, are between 1–20 meV in the considered well width range. The experimental redshifts are influenced by some meV fluctuations of both the (110) and (001) transition energies. They are, however, in good agreement with the calculation.

We present the PL linewidths of the (110) MQWs as a function of well width in Fig. 2. The solid squares are the experimental values and the lower curve represents the derivative of the calculated (110) QW transition energies. To fit the derivative to the linewidth for the 20 Å MQW, it is multiplied by an effective well width fluctuation of 3.7 Å. However, for the largest QW widths, the MQW linewidth will not go to zero, but saturate at the 1 meV linewidth of the free exciton in (110) GaAs. This is included (upper curve) by a statistical addition of the 1 meV linewidth to the MQW linewidth. The inset shows a PL spectrum of a 40 Å (110) MQW.

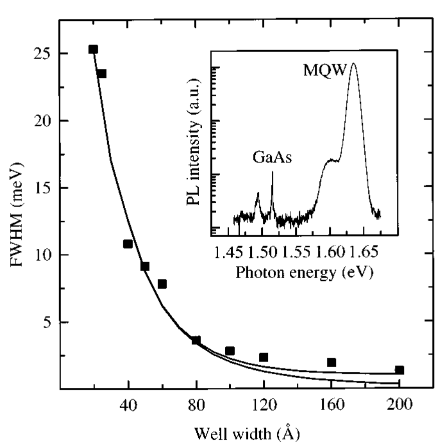

FIG. 2. PL linewidths (symbols) of (110) MQWs as a function of well width. Theoretical fits (curves) from the derivative of the calculated (110) transition energies. The upper curve includes a broadening of 1 meV from the bulk GaAs. Inset: the PL spectrum of a 40 Å (110) MQW taken at 4 K.

For most of the cases, only one sample structure has been grown, and only in exceptional cases (not shown) have we observed drastic redshifts of the (110) transition energies as reported by Nötzel *et al.*[8] The 40 Å MQW with a 11 meV linewidth, and even the 20 Å MQW with a 25 meV linewidth agree with theory to within 3 and 5 meV, respectively. The larger error in the transition energy of a 25 Å MQW corresponds to an error in the mean well width of about 1 monolayer.

We have tested the calibration of the aluminum content of two 5000 Å thick (110) $Al_xGa_{1-x}As$ samples, both with an intended mole fraction of $x = 0.30$. The PL spectra are shown in Fig. 3, where the intensities have been scaled for the sake of clarity. The bound exciton (BE) recombination[11] is observed in both samples at nearly identical transition energies, 1.888 and 1.889 eV, respectively, as determined by Gaussian linefits. However, the accuracy in the determination of the aluminum content by PL depends critically on the choice of a calibration relation for $E(\mathrm{BE})$ as a function of x.[16] Using the calibration relation[17] $E(\mathrm{BE}) = 1.512 + 1.245x$ results in the values $x = 0.302$ and 0.303, which agree with the RHEED calibration to within 1%.

Valuable information about the quality of the (110) $Al_{0.3}Ga_{0.7}As$ may be obtained from the linewidth of the BE recombination. For the optimum MBE growth of (001) $Al_{0.3}Ga_{0.7}As$, the best linewidths are 2–5 meV.[11] Compared to this, the 14 and 20 meV linewidths of the BE in the (110) $Al_{0.3}Ga_{0.7}As$ are large. The larger linewidth of the BE in one of the samples is probably caused by a 30 °C lower substrate temperature used in the growth of this sample. In our experience, the (110) growth is very sensitive to the substrate temperature: Lowering the substrate temperature by 30 °C improves the wafer surface smoothness, but enhances the dominant carbon impurity incorporation significantly. Ionized impurity concentration broadening may therefore be causing the large linewidths. For example, a BE linewidth of

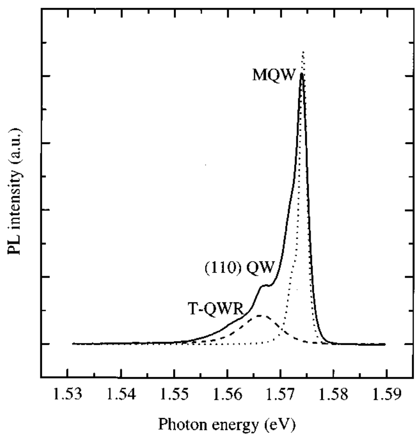

FIG. 4. PL spectrum of a 70 Å T-QWR at 4 K (full curve) with the reference spectra of the (001) structure (dotted curve), and of a 70 Å MQW grown on a cleaved GaAs substrate (dashed curve).

25 meV is expected for an impurity concentration of $\sim 10^{16}\ \mathrm{cm}^{-3}$.[11]

The PL spectrum of a 70 Å T-QWR is displayed in Fig. 4. The (001) structure was a 5000 Å GaAs buffer layer followed by 20 periods of 200 Å $Al_{0.3}Ga_{0.7}As$ barriers and 70 Å GaAs QWs. The (001) structure was cleaved in the MBE buffer chamber and overgrown on the cleaved edge with a 70 Å GaAs QW, a 200 Å $Al_{0.3}Ga_{0.7}As$ barrier, and a 100 Å GaAs cap layer. We also show the spectra of the (001) structure, and of a 70 Å reference MQW grown on a cleaved substrate which identifies the (110) oriented QW of the T-QWR structure from the nearly equal transition energies. The intensities have been scaled for the sake of clarity. In Fig. 4, the linewidth of the (110) reference grown on the cleaved substrate is 8 meV. The T-QWRs are observed with the transition energy around 1.56 eV. They are not clearly separated from the (110) QW due to the low lateral confinement energy of 7 meV and the broadening of the (110) QW. This confinement energy can be drastically improved by growing an optimized asymmetric T-QWR structure.[7]

In conclusion, the (110) $GaAs/Al_{0.3}Ga_{0.7}As$ transition energies are in good agreement with an effective mass theory using the (110) heavy-hole effective mass. The control of the mean well width is 1 monolayer and an effective well width fluctuation of 3.7 Å is derived from the PL linewidths. The growth calibration of the aluminum content of (110) $Al_{0.3}Ga_{0.7}As$ epilayers agrees within 1% with the estimate from the BE emission.

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