(110) oriented GaAs/Al0.3Ga0.7As quantum wells for optimized T-shaped quantum wires

Gislason, Hannes; Sørensen, Claus Birger; Hvam, Jørn Marcher

Published in:
Applied Physics Letters

Link to article, DOI:
10.1063/1.117896

Publication date:
1996

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
There is currently a strong interest in low-dimensional semiconductor nanostructures. By molecular beam epitaxy (MBE) cleaved edge overgrowth, 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). However, the one-dimensional confinement potentials are below 28 meV in most cases 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.

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. 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. For the overgrowth, high control of (110) oriented GaAs/AlGaAs QWs is necessary. However, the (110) growth is complicated by the lower quality of the MBE growth on (110) oriented substrates.

In this letter, we investigate the (110) oriented GaAs/Al0.3Ga0.7As 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) Al0.3Ga0.7As 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 As2-grown (110) GaAs/AlGaAs has been reported previously. 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 Al0.3Ga0.7As 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/cm²), except for the PL of the two (110) Al0.3Ga0.7As samples where an argon ion laser excitation (488 nm, 0.1 W/cm²) 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. We use \( \Delta E_g = 0.15 \) eV and \( \Delta E_c = 0.24 \) eV for the valence band and conduction band offsets.

There is currently a strong interest in low-dimensional semiconductor nanostructures. By molecular beam epitaxy (MBE) cleaved edge overgrowth, 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). However, the one-dimensional confinement potentials are below 28 meV in most cases 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.

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. 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. For the overgrowth, high control of (110) oriented GaAs/AlGaAs QWs is necessary. However, the (110) growth is complicated by the lower quality of the MBE growth on (110) oriented substrates.

In this letter, we investigate the (110) oriented GaAs/Al0.3Ga0.7As 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) Al0.3Ga0.7As 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 As2-grown (110) GaAs/AlGaAs has been reported previously. 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 Al0.3Ga0.7As 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/cm²), except for the PL of the two (110) Al0.3Ga0.7As samples where an argon ion laser excitation (488 nm, 0.1 W/cm²) 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. We use \( \Delta E_g = 0.15 \) eV and \( \Delta E_c = 0.24 \) eV for the valence band and conduction band offsets.
The derivative of the calculated experimental values and the lower curve represents the function of well width in Fig. 2. The solid squares are the measurement with the calculation.

However, for the largest QW widths, the MQW linewidth multiplied by an effective well width fluctuation of 3.7 Å. The MQW linewidth for the 20 Å MQW, it is dominated 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.

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 Nötzle et al. 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) AlGaAs 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 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 \( E(\text{BE}) \) as a function of \( x \). Using the calibration relation \( E(\text{BE}) = 1.512 + 1.245x \) results in the values \( x \approx 0.302 \) and 0.303, which agree with the RHEED calibration to within 1%.

Valuable information about the quality of the (110) AlGaAs samples may be obtained from the linewidth of the BE recombination. For the optimum MBE growth of (001) AlGaAs, the best linewidths are 2–5 meV. Compared to this, the 14 and 20 meV linewidths of the BE in the (110) AlGaAs are large. The larger linewidth of the BE is in line with the 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 to 30 °C improves the wafer surface smoothness, but enhances the dominant carbon impurity incorporation significantly. Ionized impurity concentration broadening may therefore cause the large linewidths. For example, a BE linewidth of

![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).](image1)

![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.](image2)

![FIG. 3. BE emission at 4 K from two 5000 Å thick (110) AlGaAs epilayers grown at substrate temperature of 460 °C (solid curve) and 430 °C (dotted curve), respectively.](image3)
25 meV is expected for an impurity concentration of $10^{16}$ cm$^{-3}$.

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 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.

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.

The authors acknowledge fruitful discussions with W. Langbein and D. Birkedal. This work was supported by the Danish Ministries of Research and Industry in the framework of CNAST (Center for Nanostructures).

---