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RAPID COMMUNICATION

Feedback controlled growth of strain-balanced InGaAs multiple quantum wells in metal-organic vapour phase epitaxy using an *in situ* curvature sensor

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Abstract
The growth of InGaAs quantum wells (QWs) on GaAs was optimized *in situ* using a high-resolution curvature sensor in metal-organic vapour phase epitaxy. The very small change in substrate curvature due to the incorporated strain induced by the only 6 nm thin QWs was clearly resolved and can be confirmed by strain theory. Furthermore, the possibility of *in situ* adjustment of strain compensation using a GaAsP layer is evaluated. The growth of the GaAsP layer was stopped exactly after the *in situ* curvature measurement indicated a full strain compensation by reaching the initial curvature value before growth of the QWs was started. *Ex situ* x-ray diffraction measurements confirm the exact and full strain compensation.

(Some figures in this article are in colour only in the electronic version)

We report on a quantitative study of InGaAs quantum well (QW) growth with *in situ* strain compensation by real-time strain determination using a high-resolution wafer curvature sensor. The strain compensation is performed via the exact *in situ* thickness control of the strain compensating barrier layer. This new method is of general importance, even if here InGaAs QWs grown on GaAs substrates have been used as a technologically relevant example system.

InGaAs QWs are used as an active material in high-power laser diodes in the wavelength range between 870 nm and 1200 nm [1]. Output powers of nearly 20 W from 200 μm single emitter stripes have been demonstrated at 1120 nm [2]. Due to the larger lattice constant of InGaAs as compared to the GaAs substrate, with increasing indium content an increasing amount of stress is incorporated in the layer structure. Therefore, using InGaAs QWs the maximum reachable wavelength lies around 1240 nm at a low growth temperature of 510 °C [3]. For lasers with multiple InGaAs QWs, high output powers and a good reliability can be best reached by using GaAs/GaAsP/GaAs barriers instead of GaAs barriers, because this strain compensation reduces the tendency to defect formation [2].

In situ curvature measurements have recently been reported as a very useful tool for achieving lattice matched composition in AlGaInAs distributed Bragg reflectors on InP [4] as well as for the growth of highly efficient nitride LEDs on silicon substrates [5]. First results of InGaAs QW growth with GaAsP strain compensating layers on GaAs substrates with

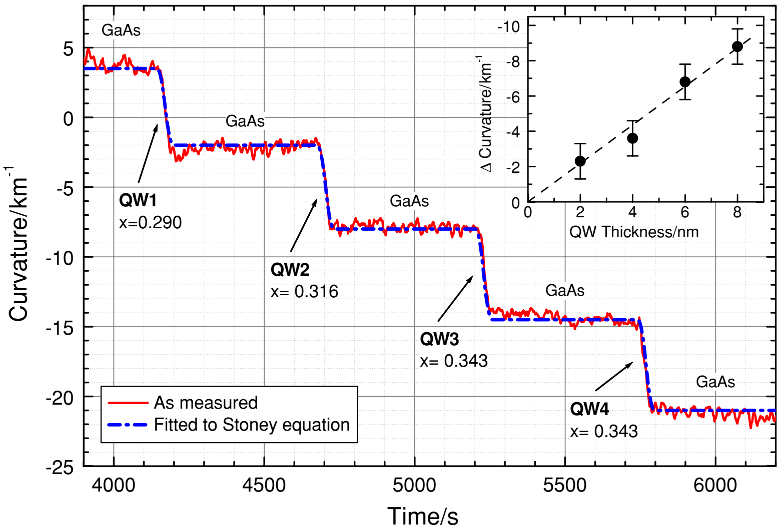

Figure 1. Wafer curvature measured during growth of four 5.5 nm thick InGaAs QWs separated by 50 nm thick GaAs barrier layers (straight line) together with the calculated curvature change (dash-dotted line) according to equations (1) and (2). The fit result for the indium content of every single QW is indicated. The inset shows the dependence of the change in curvature on the QW thickness for an indium content of $x = 0.31$ together with theory values (dashed line) obtained in a different experiment.

different thicknesses have been reported using single beam deflectometry [6].

The InGaAs multiple quantum well structures have been grown on exact oriented GaAs(0 0 1) substrates with a thickness of 350 μm in an Aixtron 200/4 horizontal metal-organic vapour phase epitaxy (MOVPE) system in single wafer configuration that is equipped with a standard optical view-port for *in situ* monitoring. The sources used are trimethylgallium, trimethylindium, arsine and phosphine. In the experiments, the InGaAs QWs and the GaAs or GaAs/GaAsP/GaAs barriers were grown at a temperature of 510 °C under otherwise optimized growth conditions as described earlier [3]. X-ray measurements for *ex situ* thickness and composition determination have been performed using a Philips Xpert system.

For the *in situ* strain measurements, a LayTec EpiCurve/HighRes sensor has been applied. This *in situ* curvature sensor has a wafer bowing resolution of $\delta(1/R_c) = \pm 0.1$ km^{-1} (R_c being the wafer bowing radius) and the related basic experimental set-up has been published in [7]. Due to wafer wobble under gas–foil rotation and other reactor related effects, we could achieve an actual real-time resolution below ± 1 km^{-1}. A positive (negative) curvature signal relates to a concave (convex) wafer bowing.

The change in the wafer bowing signal $1/R_c$ for a given InGaAs QW/GaAs structure can be calculated by Stoney's equation [8]:

$$\Delta\frac{1}{R_c} = -\frac{6h_{QW}}{h_s^2}\times\frac{M_{QW}}{M_s}\times\varepsilon_m \cong -\frac{6h_{QW}}{h_s^2}\times\frac{\Delta a_{QW}}{a_s} \cong -\frac{6h_{QW}}{h_s^2}\times\frac{a_{InGaAs}-a_{GaAs}}{a_{GaAs}} = -\frac{6h_{QW}}{h_s^2}\times x_{In} \times\frac{a_{InAs}-a_{GaAs}}{a_{GaAs}}, \qquad (1)$$

with a_{QW} and a_s being the lattice constants of the $In_xGa_{1-x}As$ QW and the substrate, respectively, and h_{QW} and h_s the respective thicknesses. M_{QW}, M_s and ε_m are the related strain moduli and the strain in the QW. For the growth of $In_xGa_{1-x}As$ on GaAs with a low indium content x_{In}, it can be assumed that $M_{QW} \approx M_s$. Therefore, a direct correlation between the curvature change and the indium content x can be obtained from equation (1).

For a complete calculation of the real growth situation, however, an initial bowing radius given by the substrate $R_c^{substrate}$ and a thermally induced bowing radius $R_c^{thermal}$ due to a temperature gradient between wafer backside (heated by the susceptor) and wafer surface (cooled by the carrier gas) have to be taken into account:

$$\left[\frac{1}{R_c}\right](t) \cong \left[\frac{1}{R_c^{substrate}}\right] + \left[\frac{1}{R_c^{thermal}}\right](T) - \frac{6}{h_s^2 a_s}\times\int_0^t \Delta a_{QW}(t) r_{QW}(t)\,dt, \qquad (2)$$

with r_{QW} being the growth rate of the QW.

Figure 1 shows the curvature measurement of the subsequent growth of four $In_xGa_{1-x}As$ QWs with a target thickness of 6 nm separated by 50 nm thick GaAs spacer layers. The used integration time of only 10 s was fully sufficient to resolve the influence of each QW on the substrate curvature. The QW growth rate was 0.2 nm s^{-1}. During growth of the GaAs barrier layers, the substrate bowing remains unchanged.

A simulation of the measured data by using equation (1) leads to a perfect agreement between curvature theory and measurement as can also be seen from figure 1. A QW thickness of 5.5 nm was used as determined by x-ray diffraction while the $In_xGa_{1-x}As$ composition x in equation (1) was used as the only fitting parameter and the lattice constants of InAs and GaAs have been corrected with the linear thermal expansion coefficients. For GaAs and InAs, room-temperature lattice constants of 0.565 325 nm [9] and 0.605 83 nm [10] and thermal expansion coefficients of 6.86×10^{-6} K^{-1} [11] and 4.52×10^{-6} K^{-1} [12], respectively, have been used for the simulation. The resulting $In_xGa_{1-x}As$ composition

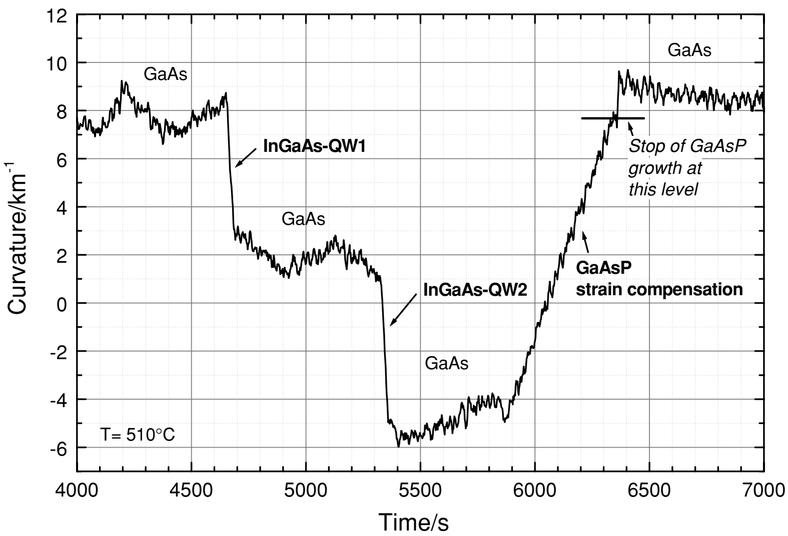

Figure 2. Development of curvature during growth of two InGaAs QWs followed by a GaAsP strain compensating layer. The growth of the strain compensating layer was stopped after the curvature has reached the initial GaAs level.

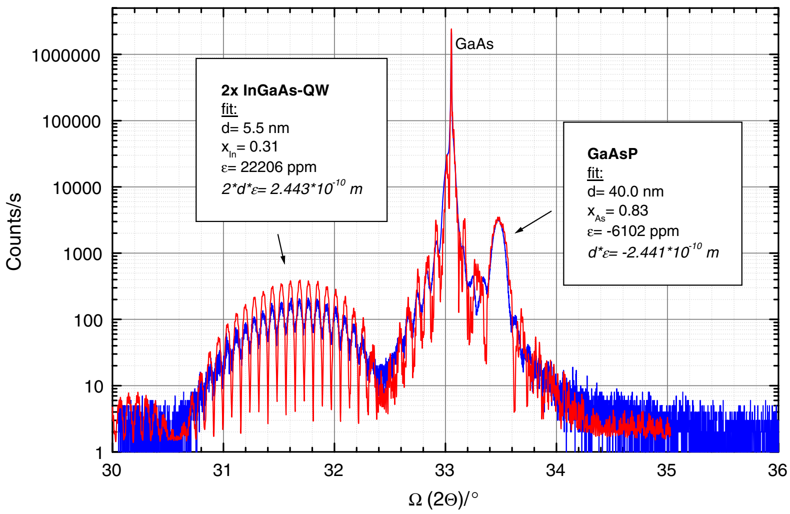

Figure 3. X-ray measurement (straight line) and fit (dotted line) of the layer structure grown in figure 2.

(as measured by wafer bowing) of the QW layers slightly increases from $x = 0.290$ for the first QW to $x = 0.343$ for the last two QWs as indicated in detail in figure 1. The average over all four QWs is $x = 0.323$. A fit to the x-ray rocking curves (not shown here) can be done by assuming either a mean indium composition of $x = 0.310$ or an increasing indium content in the following steps: 0.270, 0.305, 0.335 and 0.355. Room-temperature and low-temperature PL measurements showed a transition at 1088 nm and 1022 nm, respectively. However, an optical transition is expected only from the QW with highest indium content (i.e. lowest energy gap). Further investigations should clarify if the indium content in the QWs is really increasing—which may be explained, e.g., by indium accumulation in the reactor or a switching transient in the alkyl manifold—or if this effect shows the limits of the accuracy of the curvature measurement in its present state.

Next, we investigated the dependence of the curvature change on the quantum well thickness. The inset of figure 1 shows the dependence of the curvature change on QW thickness together with the expected behaviour as calculated from equation (1) (dotted line) for QWs with an indium content of $x = 0.31$. A linear dependence in good agreement with theory can be seen. This shows that even QWs with a thickness of below 2 nm can be resolved.

As already pointed out, a way to reduce the total strain in an InGaAs/GaAs QW structure is the introduction of $GaAs_yP_{1-y}$ strain compensation (SC) layers. For this purpose, the layer thickness and the arsenic content y of the strain compensation layer conventionally have to be adjusted by careful x-ray-based growth optimization such that the compressive stress incorporated by the InGaAs QWs is exactly balanced by the tensile stress of the GaAsP SC layer.

A more efficient alternative method of *in situ* strain adjustment is demonstrated in figure 2. The growth of two InGaAs QWs separated by a 50 nm thick GaAs spacer layer is followed by a GaAsP SC layer. As expected, the growth of the two QWs leads to a convex substrate bowing. The following growth of the GaAsP layer bows the substrate into the opposite (concave) direction due to its smaller lattice constant as compared to the GaAs substrate. Finally, growth of the GaAsP layer was stopped after the curvature effect of the QWs had been exactly compensated. During growth of the GaAs capping layer, the curvature stays constant at the initial GaAs level.

The grown *in situ* strain-compensated layer structure was afterwards investigated by *ex situ* x-ray diffraction. The corresponding rocking curve is shown in figure 3. On the left-hand side of the substrate peak, the QWs with a modulation caused by the GaAs spacer layer can be seen while on the right-hand side the GaAsP layer shows up nicely. A fit to the measured data shows that the two $In_xGa_{1-x}As$ QWs have a thickness of $h_{QW} = 5.5$ nm and an indium content of $x = 0.310$. A full strain compensation would be given for $\Sigma_{QW}\, \varepsilon_i h_i = \Sigma_{SC}\, e_k h_k$ [13]. For the layers investigated here, this results in $2 \times \varepsilon_{QW} \times h_{QW} = 2.443 \times 10^{-10}$ m for the QW. The $GaAs_yP_{1-y}$ strain compensation layer has a thickness of $h_{SC} = 40.0$ nm and an arsenic content of $y = 0.83$ which results in $\varepsilon_{SC} \times h_{SC} = -2.441 \times 10^{-10}$ m. This verifies that a full and exact strain compensation was reached by using the *in situ* adjusted strain compensation layer.

In summary, by applying a high-resolution wafer curvature sensor we have developed a new *in situ* method for measuring the indium composition of InGaAs quantum wells embedded in GaAs. The quantitative analysis has been performed by using straightforwardly Stoney's strain theory. Improving the experimental set-up, a resolution of about $\Delta x_{In} = 0.005$ is expected based on a curvature resolution of $0.1\ km^{-1}$. Furthermore, we have demonstrated *in situ* controlled strain compensation by GaAsP after QW growth. The layer thickness of the GaAsP layer controlled by the curvature measurement led to an exact strain compensation as shown by x-ray measurements.

Acknowledgments

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