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Report:

It has been shown recently /1,2/ that a lateral carrier confinement can be introduced into an InGaAs-quantum well (QW) by lateral patterning of an InGaP stressor layer grown on top of it. For device applications, however, a planarization of the structure in a second epitaxial step is needed. Finite element calculations (FEM) of the strain field distribution have shown that an overgrowth of the QW-stressor system reduces the strain introduced into the QW. Overgrowth using a complementary strained material with respect to the stressor layer may be a way to keep the strain in the QW high. But it is also known from our previous studies /3/, that ternary alloys show a tendency to self organization during growth accompanied with high local strain modifications and can even lead to large structural defects.

To study the strain behavior after overgrowth and its impact on the optical properties of the InGaAs-QW two samples with identical lateral patterning (1000 nm grating period, ridge to valley ratio of 2.7) and identical vertical layer structure (10 nm thick compressively strained InGaAs-QW, $\varepsilon = -1.1$ %, 10 nm thick GaAs etch stop layer, 110 nm thick tensile strained InGaP, $\varepsilon = 0.3$ % and 10 nm thick GaAs cap layer) were overgrown in a second step by metal-organic vapor phase epitaxy (MOVPE).

One sample was overgrown with 96 nm GaAs whereas the other was overgrown with 75 nm compressively complementary strained InGaP up to a planar surface. The optical properties were studied by 10 K photoluminescence (PL).

An overgrowth with the complementary strained InGaP layer lead to a loss of the strain induced PL line shift of the QW in comparison with the free standing stressor grating structure; the induced strain is compensated. But in the case of overgrowth with GaAs the PL wavelength becomes even shorter. To understand this “overcompensation” behavior a detailed investigation of the strain distribution was necessary.

As in the previous experiment at ID 10B (SI 488) we used the vertical sample setup to measure grazing incidence diffraction (GID). This way we were able to obtain information about the 3D strain distribution exploiting the depth sensitivity by changing the angle between the incoming beam and the sample surface (α_i). Measurements around the strain sensitive longitudinal (200) reflection (equivalent to the (220) reflection in cubic notation) were carried out.
In Fig. 1 the longitudinal scans at different α_i are shown for the free standing patterned sample A (Fig. 1a), the same sample overgrown with GaAs (sample A-GaAs, Fig. 1b) and the same sample overgrown with compressively strained InGaP (sample A-InGaP, Fig. 1c).

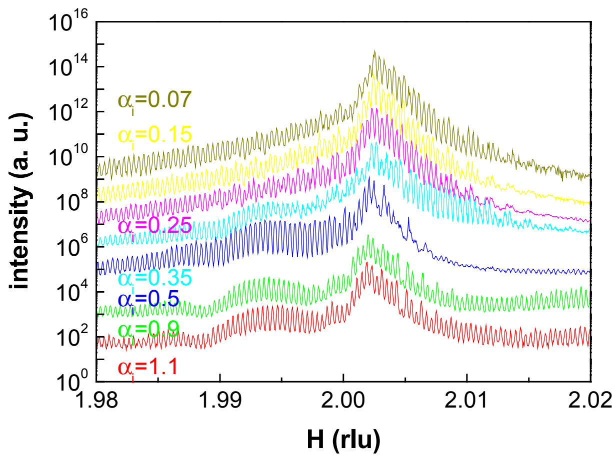

Fig. 1a free standing stressor grating

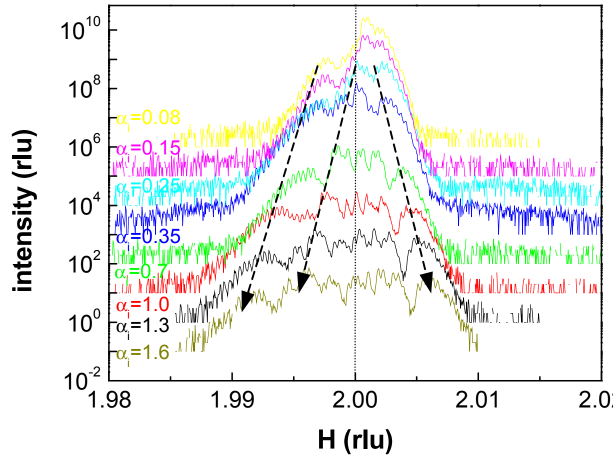

Fig. 1b overgrowth with GaAs

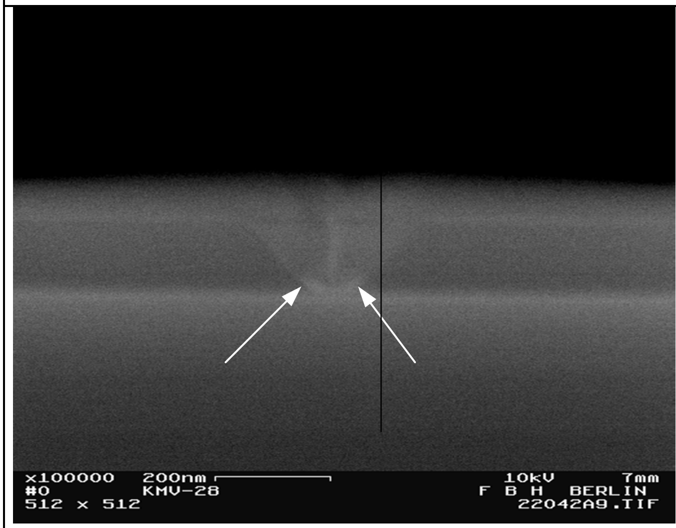

Fig. 2 SEM picture of overgrowth with InGaP

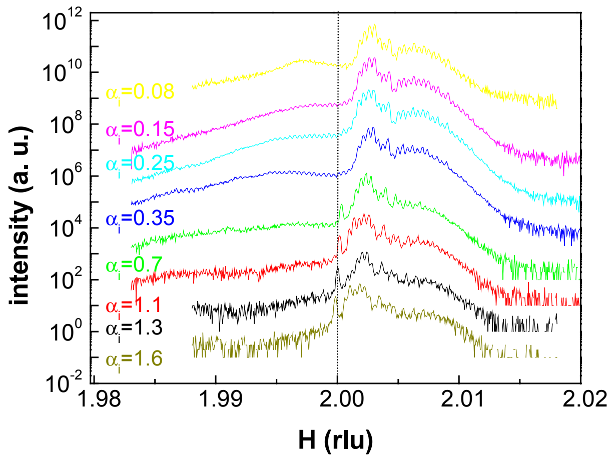

Fig. 1c overgrowth with InGaP

In Fig. 1a it can be seen that the first three scans (α_i = 0.07 deg - 0.25 deg) are very similar due to very small penetration depth of the X-ray beam (Λ = 3 - 10 nm). The dominating feature is the intensity maximum at 2.0025 rlu which is originated by the relaxation of the strained InGaP at the free surfaces. The total strain (ε_τ) amounts to -0.127 % indicating that the pseudomorphic strain of the InGaP (ε = 0.3%) is not fully relaxed. With deeper penetration into the sample the maximum shifts closer to the position of the GaAs substrate (H = 2 rlu). Starting from α_i = 0.35 (Λ of about 100 nm) an additional peak emerges at H=1.992 rlu which is due to the strained region below the valley. Here an additional tensile strain of ε_τ = 0.3 % is found, caused by the relaxing InGaP stressor layer. This is in good agreement with the FEM predictions and PL-results.

For the sample overgrown with GaAs the GID-scans look much more complicated. Contrary to the previous sample the intensity maximum is observed close to H = 2 rlu. Similar to the freestanding sample the first 3 scans (α_i = 0.07deg - 0.25deg, Λ = 1 - 10 nm) are almost identical indicating that we do not observe surface related phenomena. Even at this depth in the GaAs cap layer strain features appear; a larger part is compressively strained (ε_τ = -0.1 %, see additional peak on the right hand side of the maximum) and also some tensile strained GaAs is observed (ε_τ = 0.1 %). However, a substantial part of the GaAs at this depth is unstrained and is probably located on top of the ridges. Up to a depth of the QW (α_i = 0.7 deg, Λ = ~200 nm) the compressive strain dominates. This could explain the blue shift of the QW-PL line. With increasing depth (α_i = 1.0, Λ = ~500 nm), well below the QW, the maximum of intensity shifts to values lower than H = 2 rlu pointing to an increasing tensile strain (see arrows in Fig. 1b). The intensity of the side maxima becomes equal and the compressive as well as the tensile strain become larger (see dashed arrows). SEM and TEM investigation showed that near the edges of the valley bottom a segregation of In took place. However, it can be stated that the persisting grating peak oscillations which can be seen in the entire range of the GID scans indicate sharp interfaces and good crystalline quality of the GaAs overgrown sample.

The striking feature in the GID scans from the sample overgrown with InGaP is, that the shape of the scans does not changes with penetration depth (see Fig. 1c). The maximum of intensity is located at H = 2.003 rlu indicating $a_{II} < a_{GaAs}$ by -0.16%. Already near the sample surface a broad side maximum (ε_τ = -0.3 %) is observed. This maximum dominates in all GID scans and no additional strain features appear with larger depth. This behavior can be explained by self organization effects during the InGaP cap layer growth. The strain caused by the InGaP stressor layer is compensated by this self organizing process. Figure 2 shows a SEM picture where a region with bright contrast at the bottom of the valley appear (see arrows in Fig. 2). As in the case of the sample overgrown with GaAs an out-diffusion of In from the grating sidewalls followed by In-segregation at the valley bottom during growth took place. This In-rich alloy leads to an additional tensile strain in the QW because of its larger lattice constant.
Besides this segregation region at the bottom another bright region in the middle of the groove appeared. This is a behavior which is known from AlGaAs overgrowth over a GaAs surface grating resulting in a vertical quantum well /3/. In our case this vertical quantum well like structure consists of an In rich alloy. The diffraction pattern shows a strong damping of the grating peaks indicating a disruption of the wave fields due to a large number of defects in the sample. This was confirmed by TEM investigations.

The strain distribution in such a complicated structure is difficult to model by FEM calculations. Further effort is necessary to extract the information about the 3D strain distribution from the measured GID scans.

To understand the complicated strain distributions in the overgrown samples further investigations, especially rod scans (Q_z-scans) at different incidence α_i angles are necessary. Only a combination of different methods (X-ray diffraction, GID, electron microscopy and spatially resolved PL) can answer the questions about the 3D strain distribution in such complicated samples.

[1] U. Zeimer, J. Grenzer, U. Pietsch, ESRF Report SI-488 (2001).
[2] U. Zeimer, F. Bugge, S. Gramlich, V. Smirnitski, M. Weyers and G. Tränkle, J. Grenzer, U. Pietsch, G. Cassabois V. Emiliani and Ch. Lienau, *Appl. Phys. Lett* **79**, 1611 (2001).
[3] U.Pietsch, U.Zeimer, L.Hoffmann, J.Grenzer, S.Gramlich, Mat. Res. Proc. **Vol. 618**, 41 (2000).