2.16 Transmission-electron-microscopy study of Sb-based quantum dots

There is a strong demand for the development of mid-infrared lasers for the detection of various chemical, explosive, and biological agents, which have pronounced absorption lines in the wavelength range of 3–5 μm. InSb-based quantum dots (QDs) represent a promising active medium for optoelectronics devices operating in the mid-IR region. Despite the lattice mismatch of about 6.3%, which is comparable to the well known InAs/GaAs case, the realization of Sb-based nanostructures is still challenging. The growth of high-quality InSb QDs in GaSb has not been successful, irrespectively of the epitaxial growth technique. The problem arises from the comparatively weak In-Sb binding energy being responsible for a long migration length of In adatoms on Sb-terminated surfaces and thus for the formation of large and relaxed InSb islands. We have developed a growth method consisting of an InSb deposition at extremely low temperatures followed by a properly designed annealing step.

The samples were grown on *n*-type GaSb(001) substrates by solid-source molecular-beam epitaxy (MBE) using As- and Sb-valved cracker cells. Uncapped InSb islands and dedicated heterostructures with the QDs inserted in the centre of a GaSb barrier layer, confined on both sides by an AlGa(As)Sb cladding, were structurally investigated by transmission electron microscopy (TEM).

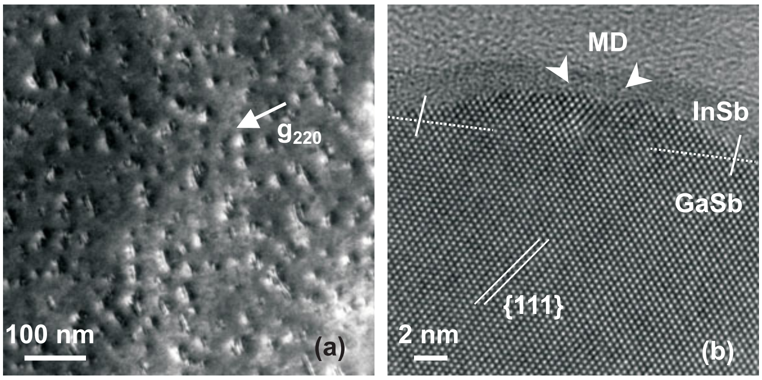

Fig. 41. (a) Plan-view (220) dark-field TEM image of partially strain relieved InSb islands grown on GaSb (001) at 250 °C and (b) HRTEM image showing pure edge-type misfit dislocation at the interface.

Figure 41(a) displays a plan-view TEM image of an uncapped InSb layer of nominal 2.5 monolayers (ML) thickness grown at 250 °C followed by annealing. The surface morphology is characterized by small and flat InSb islands reflecting a mono-modal size distribution with an average diameter of about 20 nm. Based on the strain-sensitive imaging condition (with $\mathbf{g}_{220}$ reflection), we found that most of the islands are relaxed by misfit dislocations. The high-resolution TEM (HRTEM) image in Fig. 41(b) demonstrates the presence of a misfit dislocation (MD) in the center of the island being of pure edge-type with a Burgers vector $\mathbf{b} = 1/2[1\bar{1}0]$, which is most efficient in strain relief. Because of the sessile character of the dislocation we assume that its formation proceeds during the annealing process, when the InSb islands are formed on the free surface. Additionally, the TEM analysis determines a critical island size of about 12 nm for the onset of plastic relaxation.

The situation is completely different when diffusion and strain relief is inhibited in structures, where the InSb is capped by a thin GaSb layer before annealing. Figure 42(a) shows

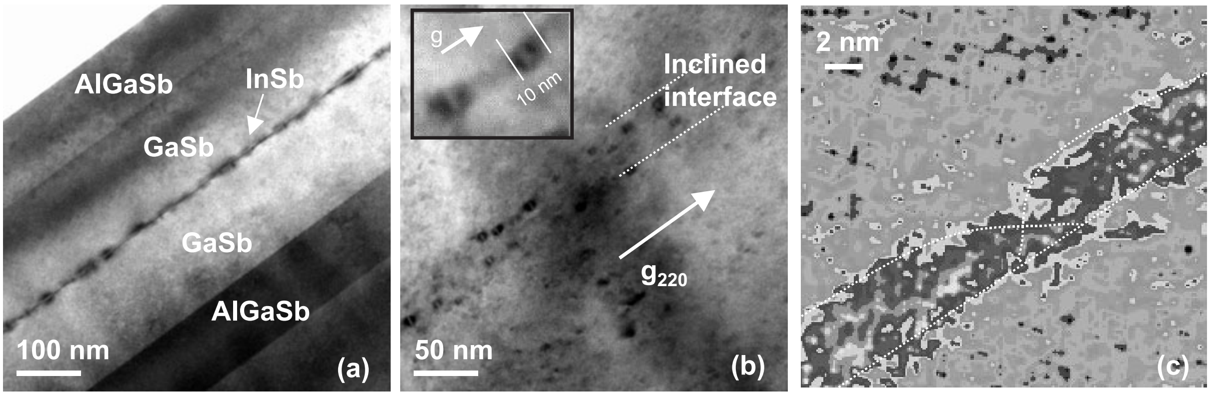

Fig. 42. (a) Bright-field XTEM image showing the layer structure of a sample with clearly visualized InSb layer. (b) Bright-field (220) TEM image showing QDs with almost the same size (≈ 10 nm including strain-field). (c) Lattice distortion analysis of an HRTEM image showing QDs.

a (002) bright-field cross-sectional TEM (XTEM) image of a buried QD sample. The strong contrast variations along the InSb layer compared to the homogeneous contrast of the adjoining GaSb demonstrate the existence of a wetting layer with a high density of QDs. Note that the complete structure is free of any extended defects and that no threading dislocations are observed. By tilting the sample around the [110] axis, the interface becomes inclined to the electron beam, which enables the observation of the isolated InSb QDs. Applying the **g** = 220 diffraction condition, the strain field of the QDs was detected in this direction revealing an average size of about 10 nm. In detail, the lattice strain around the InSb QDs appears as lobes of dark contrast (low intensity) with lines of no contrast perpendicular to **g** [the so-called coffee bean contrast, more evident in the inset of Fig. 42(b)]. These particular strain effects correspond to fully strained InSb QDs with almost spherical shape. Further details about the QD structure along the growth direction were obtained from the lattice distortion analysis taken from HRTEM images. This technique detects the tetragonal distortion of the lattice with respect to an undisturbed reference lattice, here the GaSb barrier layer. The amount of tetragonal distortion was plotted in a gray-scale representation as shown in Fig. 42(c). The result demonstrates the existence of a continuously strained wetting layer (sharp lower interface) together with the undulation in the upper interface indicating the three-dimensional shape of the QDs.

In summary, we performed TEM investigations of InSb QDs in GaSb grown by an alternative MBE growth procedure. We observed that the size of the buried QDs is smaller than the one of uncapped QDs. In addition, uncapped, but relaxed QDs appear flat, while buried QDs are more spherical. The strain relaxation process in the buried QDs is delayed resulting in perfectly strained QDs due to the fact that the In-adatoms mobility during annealing is strongly reduced by the cap layer.

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