Growth, atomic structure, and type-II band alignment of GaSb/GaAs nanostructures: Quantum wells, dots, and rings

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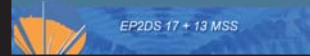
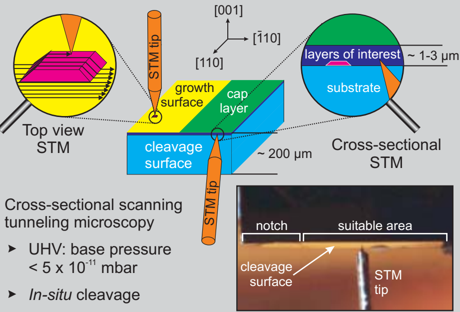


XSTM experiment



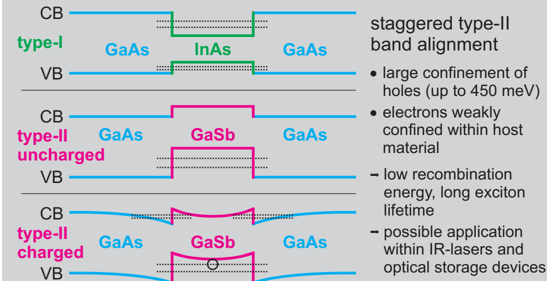
Cross-sectional scanning tunneling microscopy

- UHV: base pressure $< 5 \times 10^{-11}$ mbar
- *In-situ* cleavage

Conclusion

- Formation of quantum rings
- Outer contour: truncated pyramid, ~ 10 - 20 nm base length, 1 - 2.5 nm height
- Inner ring diameter up to 10 nm
- Strong segregation of Sb during overgrowth, Sb - As exchange processes
- Confirmation of type-II band alignment by spectroscopy
- Quantum rings especially interesting for charge storage

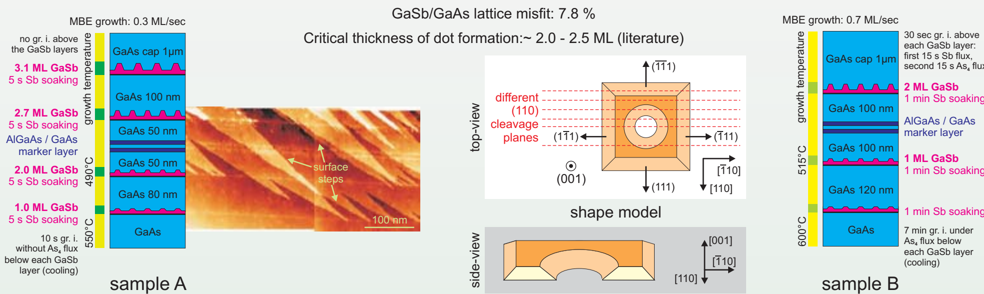
GaSb/GaAs quantum dots

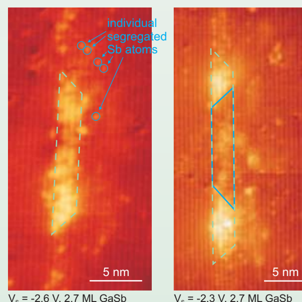


staggered type-II band alignment

- large confinement of holes (up to 450 meV)
- electrons weakly confined within host material
  - low recombination energy, long exciton lifetime
  - possible application within IR-lasers and optical storage devices

Ring-like quantum dot structure

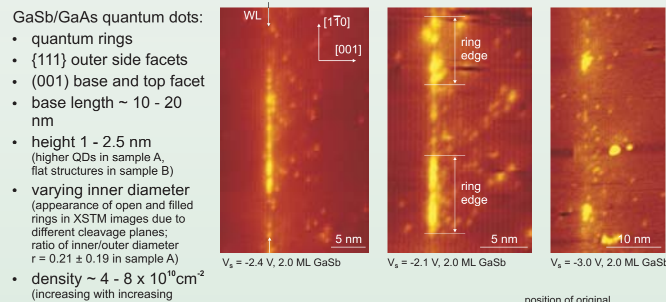




V_s = -2.6 V, 2.7 ML GaSb V_s = -2.3 V, 2.7 ML GaSb

GaSb/GaAs quantum dots:

- quantum rings
- {111} outer side facets
- (001) base and top facet
- base length ~ 10 - 20 nm
- height 1 - 2.5 nm (higher QDs in sample A, flat structures in sample B)
- varying inner diameter (appearance of open and filled rings in XSTM images due to different cleavage planes; ratio of inner/outer diameter r = 0.21 ± 0.19 in sample A)
- density ~ 4 - 8 x 10^{10} cm^{-2} (increasing with increasing

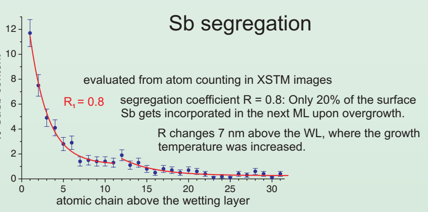


V_s = -2.4 V, 2.0 ML GaSb V_s = -2.1 V, 2.0 ML GaSb V_s = -3.0 V, 2.0 ML GaSb

segregated Sb atoms · GaSb wetting layer · 10 nm · diluted $GaSb_{0.25}As_{0.75}$ QD with segregated Sb atoms · 5 nm

V_s = -2.5 V, 1.0 ML GaSb V_s = -2.4 V, 2.7 ML GaSb

Sb segregation



evaluated from atom counting in XSTM images

segregation coefficient R = 0.8: Only 20% of the surface Sb gets incorporated in the next ML upon overgrowth.

R changes 7 nm above the WL, where the growth temperature was increased.

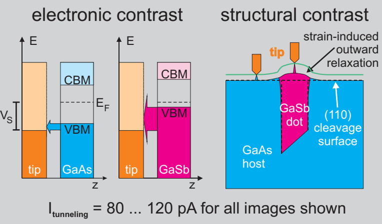
position of original soaking layer · restgas adsorbates · tip artefacts · V_s = -2.7 V · 10 nm · Sb atoms are marked

GaSb layer induced by Sb soaking

- Sb - As exchange processes at the growth surface (Sb soaking)
- Sb-rich GaSb surface reconstruction
- GaSb bond weaker than GaAs

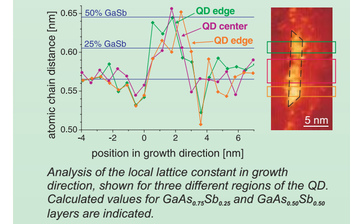
strong Sb segregation during overgrowth
\+ high strain in GaSb/GaAs nanostructures
⟶ formation of quantum rings upon capping

Image contrast



$I_{tunneling}$ = 80 ... 120 pA for all images shown

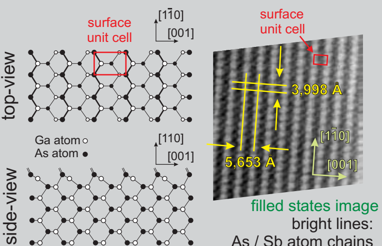
Chemical composition



Analysis of the local lattice constant in growth direction, shown for three different regions of the QD. Calculated values for $GaAs_{0.75}Sb_{0.25}$ and $GaAs_{0.50}Sb_{0.50}$ layers are indicated.

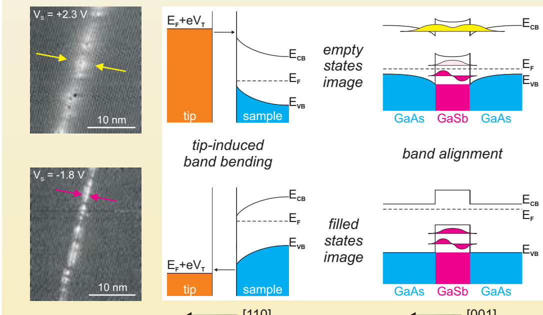
varying stoichiometry within the nanostructures, ranging from Qds with low GaSb content (~30%) up to regions of locally pure GaSb

GaAs(110) surface



filled states image
bright lines: As / Sb atom chains

Electronics: type-II band alignment



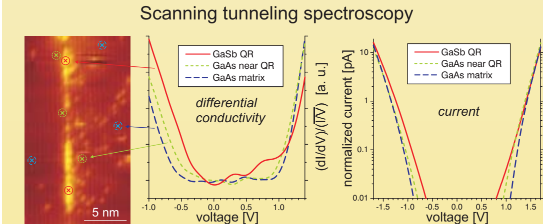
different appearance of GaSb/GaAs layer depending on bias polarity:

- broadly smoothened at positive V_s
- sharply defined at negative V_s

two electric-field effects:

- tip-induced band bending, perpendicular to cleavage surface
- additional band bending in growth direction, i. e. parallel to surface, due to type-II band alignment

Scanning tunneling spectroscopy



I-V and dI/dV-V spectra at different positions of the sample: differential conductivity (dI/dV)/(I/V) proportional to LDOS

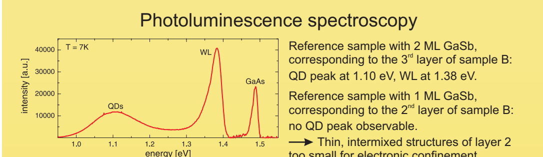
- smaller absolute band gap on GaSb than on GaAs
- shifted curve for negative sample voltages
  - valence-band offset
  - hole localization energy ~ 0.3 eV
- slightly shifted curve for positive sample voltages
  - type-II conduction band offset
- additional contribution at GaSb for small positive voltages (see below)
  - hole occupation of GaSb QDs due to type-II band alignment and tip-induced band bending

Three different tunneling conditions at small positive bias:

- tunneling into depleted GaSb VB states
  - charging of the QD (hole occupation)
- no current at GaAs matrix
- tunneling through GaAs space charge region near GaSb

tunneling at small positive sample voltage · tip · GaSb QD · tip · GaAs · tip · GaAs near GaSb

Photoluminescence spectroscopy



Reference sample with 2 ML GaSb, corresponding to the 3rd layer of sample B: QD peak at 1.10 eV, WL at 1.38 eV.

Reference sample with 1 ML GaSb, corresponding to the 2nd layer of sample B: no QD peak observable.

⟶ Thin, finished structures of layer 2 too small for electronic confinement

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