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Unified description of the formation and evolution of self-organized quantum dots in the InAs/GaAs(001) and Ge/Si(001) systems

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Self-organised semiconductor quantum dots, epitaxially grown on lattice-mismatched substrates, are promising candidates for the practical realisation of “artificial atoms.” Their peculiar tuneable properties open the way to novel applications in the fields of optoelectronics, single-electron and single-photon devices as well as quantum computation. However, a successful implementation requires a precise control over their shapes and sizes which, at present, is still an open problem. Its solution needs a basic understanding of the actual morphology of the quantum dots and of their further evolution during post-growth treatments. Here, by means of high-resolution scanning tunnelling microscopy, we investigate the model systems of self-organised quantum dots formed from single and binary semiconductor compounds, Ge grown on Si(001) substrates and InAs on GaAs(001), respectively. We demonstrate that for experimental conditions close to the thermodynamic limit (high substrate temperatures and low deposition rates) only two families of faceted and defect-free nanocrystals exist, small pyramids composed of four equivalent shallow facets, and larger multifaceted domes. The analogies between the two material systems extend also to the existence of hut-clusters and embryo islands that act as precursors for pyramid. A shape transition from pyramids to domes is seen to occur in both material systems. The transformation path, essentially consisting of the bunching of incomplete facets at the top of pyramids larger than a critical size, is precisely determined for Ge/Si(001) and explained in terms of surface diffusion processes only. These striking similarities further extend to the capping procedure that is needed in order to transform self-organised islands into true quantum dots. For both material systems we observe a backward dome to-pyramid transition accompanied by a strong height decrease. This complex phenomenology is rationalized in terms of intermixing processes driven by strain release. Our measurements suggest that the unified picture we are presenting for the prototype systems Ge/Si(001) and InAs/GaAs(001), extends, at least qualitatively, to a large number of material combinations that follow the Stranski-Krastanow growth mode.