Kinetics of the evolution of InAs/GaAs quantum dots to quantum rings

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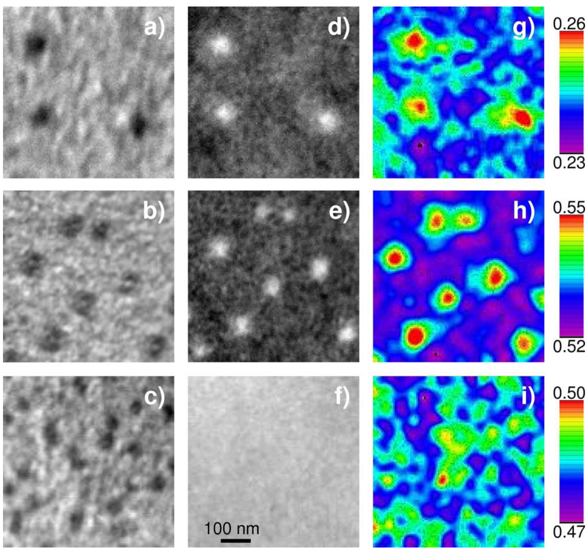
The quantum confinement properties of self-assembled quantum dots (QDs) can be deeply mutated by deposition of a thin layer of the barrier material in appropriate conditions and a subsequent annealing, modifying them into so-called quantum rings (QRs) [1]. Thanks to their unique shape, self-assembled QRs possess different electron confinement properties, and thus optical and transport properties, with respect to QDs. As a result, self-assembled QRs can be viewed as a size bridge between mesoscopic and molecular ring structures.

A number of experimental studies were concerned with the formation mechanism of InAs/GaAs QRs. The conventional method for the formation of InAs/GaAs QRs is a capping and annealing procedure. During the annealing of the partially capped QDs, a strong material intermixing and redistribution toward the surrounding wetting layer region takes place. Despite this standard recipe for growing QRs by molecular beam epitaxy has been developed, their formation mechanisms are far from being understood, and only some qualitative models have been proposed; thus questions such as the kinetics of the dot-to-ring transition, and the shape and composition of the nanostructures in the limit of thermodynamic equilibrium are still a matter of debate.

In our previous work, we have successfully studied the composition distribution of individual surface InAs/GaAs QRs by chemical maps of single nanostructures obtained by means of laterally resolved photoelectron spectroscopy [2]. In particular, we found that the composition of QRs is not uniform, being In-rich at the center region, corresponding to the residual dot material imaged in buried rings. Our earlier observations on InAs/GaAs QDs suggest that the dot surface composition is neither pure InAs nor homogeneous $In_xGa_{1-x}As$, but present an In concentration increasing from the borders to the center of the dots [3].

Here we present an experimental study of the dot-to-ring evolution in the InAs/GaAs system, as a function of annealing time after deposition of the GaAs cap layer, aimed at understanding the kinetics of the transition, and the thermodynamic equilibrium limit. Surface profile changes measured by atomic force microscopy (AFM) are correlated with shifts in photoluminescence emission. By using x-ray photoemission electron microscopy (XPEEM), we obtain two-dimensional compositional maps of unburied rings, which we relate to the surface topography measured by AFM. Our results show a progressive dissolution of the original dot, with the outdiffused material forming a second wetting layer on the planar region surrounding the dot. For the longest annealing time, in a situation close to thermodynamic equilibrium, no residual dot material is left in the holes, and an In-rich layer covers uniformly the surface. Our observations are interpreted in terms of surface chemical potential distribution, where the wetting term is reconsidered in view of the measured surface composition maps.



(a–c) 500x500 nm² low energy electron microscopy (LEEM) images of sample surface for 0, 30, and 120 s annealed samples, respectively. (d–f) XPEEM images from the same surface regions measured at kinetic energies corresponding to the In 4d core level, with a photon energy of 80 eV. (g–i) Surface In concentration maps of the same regions measured by LEEM and XPEEM. Grayscales in images (a)–(f) are chosen to optimize the contrast, while color scales for images (g)–(i) are indicated at the right.

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