Surface dynamics of III-V semiconductors studied by *in situ* synchrotron x-ray diffraction during molecular beam epitaxy

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We investigate the surface kinetics during growth and recovery of III-V compound semiconductors using a dedicated beamline at the synchrotron BESSY in Berlin, Germany. The experiment combines x-ray diffraction in the 6—12 keV wavelength range with a molecular beam epitaxy (MBE) system that is capable of growing a variety of III-V materials. In contrast to other diffraction methods, x-ray diffraction data can be quantitatively analyzed using kinematical theory. This allows us to compare our results with established theoretical models that describe the kinetics on crystal surfaces under MBE conditions.

We have investigated the homoepitaxy of GaAs, InAs and GaSb on the (001) face. On GaAs, shown in Fig. 1, we can fit the x-ray diffraction peak profiles with Voigt functions consisting of a Gaussian resolution function and a Lorentzian, implying an exponential island size distribution and scaling. The resolution can be determined independently from the width of nearby bulk reflections, allowing us to fit the profiles with a minimum number of parameters. The integrated peak intensity (Fig. 1(c)) is constant during the entire experiment, implying that the surface reconstruction does not change. Since the island size approaches the resolution of the diffractometer at late times, the peak intensity shown in Fig. 1(b) saturates at late times. The peak intensity therefore is proportional to the island size only at early times. The mean island size determined from the fits (Fig. 1(d)) reveals a *linear* coarsening of the 2D islands. This contradicts the established Ostwald ripening model, which predicts an exponent of 1/3 instead of 1, as well as a peaked island size distribution instead of an exponential one.

On InAs (001), we find an azimuthal dependence not only of the average island size like on GaAs, but also of the island size distribution. An example of two reflections that make a 90 ° angle are shown in Fig. 2. The same behavior is present during the recovery phase after growth, although the current state of our analysis indicates that it does not strictly scale. The coarsening exponents on InAs (001) are around 1/3. Together with the peaked island size distribution, at least in one dimension, this lets us conclude that InAs is closer to the generic Ostwald ripening case.

GaSb, at least at the low temperatures shown in Figs. 3 and 4, exhibits an extremely slow recovery. The peak profiles (Fig. 3) again show a split-peak shape, indicating a behavior close to Ostwald ripening. The small coherent peak in the figure is due to the fact that the coverage is slightly off from 0.5. The slow recovery does not imply that the surface kinetics is slow, which is easily seen from the data in Fig. 4. Here, the deposition is interrupted several times, demonstrating that the slow recovery does not contradict the presence of growth oscillations with large amplitude and low damping, generally identified with high adatom mobility.

Comparing the three different surfaces, it becomes clear that the coarsening exponent is not a generic parameter that is universal for whole classes of materials. Instead, we find drastically different behavior on materials that share common elements and have very similar properties. The comparison of these three examples forces us to conclude that parameters like the coarsening exponent that one may think to be universal, strongly depend on the detailed configuration of a surface and the kinetics on the atomic level.

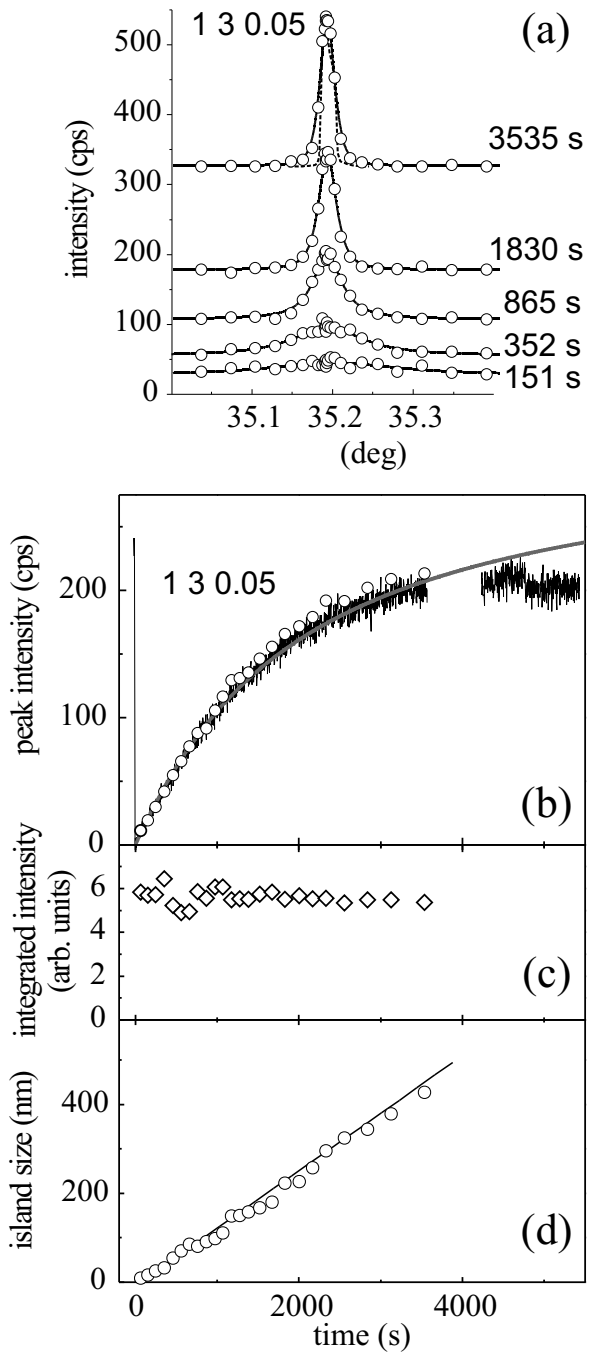

Figure 1: Recovery after the deposition of 0.5 ML of GaAs on GaAs (001). Voigt function fits (a) to the reflection profiles yield a constant integrated intensity (c) and a *linear* coarsening of the 2D islands (d). The intensity of the peak maximum as a function of time is shown in (b).

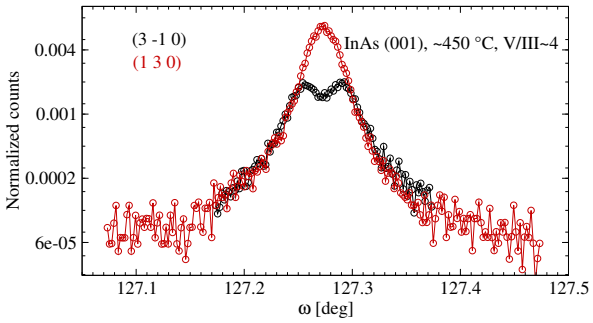

Figure 2: On InAs (001), the island size distributions along two orthogonal directions on an annealed surface are distinctly different.

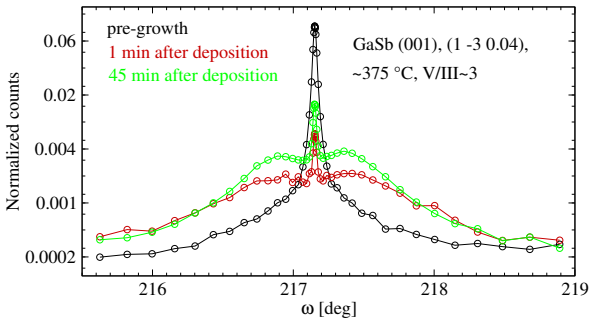

Figure 3: Three diffraction profiles before and after deposition of 0.5 ML on GaSb. Black: annealed surface before deposition, red: ≈1 min after deposition, green: 45 min after deposition.

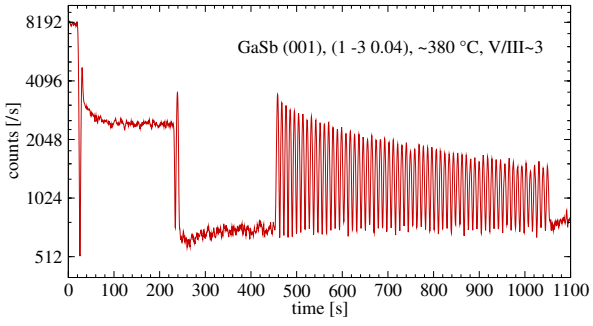

Figure 4: Interrupted diffraction oscillations during the deposition of GaSb. The low damping of the oscillations implies a high adatom mobility, yet recovery is extremely slow.