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# Effect of a lattice-matched GaAsSb capping layer on the structural properties of InAs/InGaAs/InP quantum dots

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The influence of a lattice-matched GaAsSb capping layer on the structural properties of self-assembled InAs quantum dots (QDs) grown on InP substrates is studied on the atomic scale by cross-sectional scanning tunneling microscopy. While lattice-matched $In_{0.53}Ga_{0.47}As$-capped QDs are clearly truncated pyramids, $GaAs_{0.51}Sb_{0.49}$-capped QDs grown under the same conditions look like full pyramids and exhibit a larger height, indicating that capping with GaAsSb reduces dot decomposition. Since there are no differences in strain between the two capping layers, this behavior is most likely related to the surfactant effect of Sb, which stabilizes the growth front and avoids adatom migration. © *2010 American Institute of Physics*. [doi:10.1063/1.3361036]

## I. INTRODUCTION

There is nowadays a very strong interest in Sb-related materials in the field of quantum dots (QD).[1–11] In particular, (In)GaAsSb capping layers have been used to extend the emission wavelength of InAs QDs grown on GaAs substrate to the 1.55 $\mu$m region.[1–5] The structural properties of these QDs have been shown to be significantly different from those of GaAs-capped QDs. QDs capped with $GaAs_{0.78}Sb_{0.22}$ exhibit a full pyramidal shape and a much bigger height than GaAs-capped QDs, due to the fact that GaAsSb prevents dot decomposition during capping.[12] The reason for this is still unclear and it is very difficult to separate the chemical effects from the strain related effects since GaAsSb acts as a strain reducing layer for InAs/GaAs QDs. Upto now, Sb-containing layers have been used as capping layers only in GaAs-based QDs. Nevertheless, GaAsSb can be grown lattice-matched to InP, which allows to rule out the strain reducing layer effects. It is therefore very interesting to investigate which is in this case the effect of a GaAsSb capping layer. In addition, InAs QDs grown on InP substrates capped with GaAsSb allow to extend laser emission wavelength achievable on InP and to reach the technologically important transparency atmosphere windows in the mid infrared.[13]

In this work, we have used cross-sectional scanning tunneling microscopy (X-STM) to analyze, at the atomic scale, how capping with lattice-matched GaAsSb influences the structural properties of InAs QDs grown on (311)B InP substrates. The QD size, shape, and composition are determined and are compared to the case of lattice-matched InGaAs capping.

## II. EXPERIMENTAL DETAILS

The samples were grown by solid source molecular beam epitaxy on $n^+$ Si doped (311)B InP substrates. Two QD layers were grown in the same sample under the same conditions by depositing 2.5 ML of InAs on lattice-matched $In_{0.53}Ga_{0.47}As$ buffer layers. The first QD layer (reference layer) was capped with a 50 nm thick lattice-matched $In_{0.53}Ga_{0.47}As$ layer, and the second with 50 nm of lattice-matched $GaAs_{0.51}Sb_{0.49}$. The growth temperature was set at 450 °C during the whole growth runs. Before the InAs deposition, a growth interrupt (GI) under arsenic was performed during 25 s in order to smooth the growth front before QD formation. For the first QD layer, a GI under arsenic of 25 s was performed before the growth of the InGaAs capping layer. For the second QD layer, before the growth of the GaAsSb capping layer, a GI under arsenic of 25 s followed by a GI of 3 s under both arsenic and antimony fluxes were performed in order to ensure similar QD formation conditions for both layers. The antimony beam equivalent pressure was set at $7.2\times10^{-7}$ Torr. In order to achieve high composition control during the growth of GaAsSb alloy, the V/III ratio was maintained close to unity. X-ray diffraction measurements were performed on test samples to control the GaAsSb and InGaAs layer lattice matching conditions. The reference capping material is chosen to be InGaAs and not InP in order to avoid differences induced by the As/P exchange reaction, present when capping with InP.[14]

The X-STM measurements were performed at room temperature on the $[01\bar{1}]$ surface plane of *in situ* cleaved samples under UHV ($p<4\times10^{-11}$ Torr) conditions. Polycrystalline tungsten tips prepared by electrochemical etching were used. All the images shown in this paper were obtained in constant current mode at negative voltage (filled states) so the group V elements (As and Sb) are directly imaged.

## III. RESULTS AND DISCUSSION

Figure 1(a) shows a filled states image of the two QD layers. The separation between the two layers is 52 nm, in good agreement with the nominal 50 nm. One difference between the two cases can already be observed in this image,

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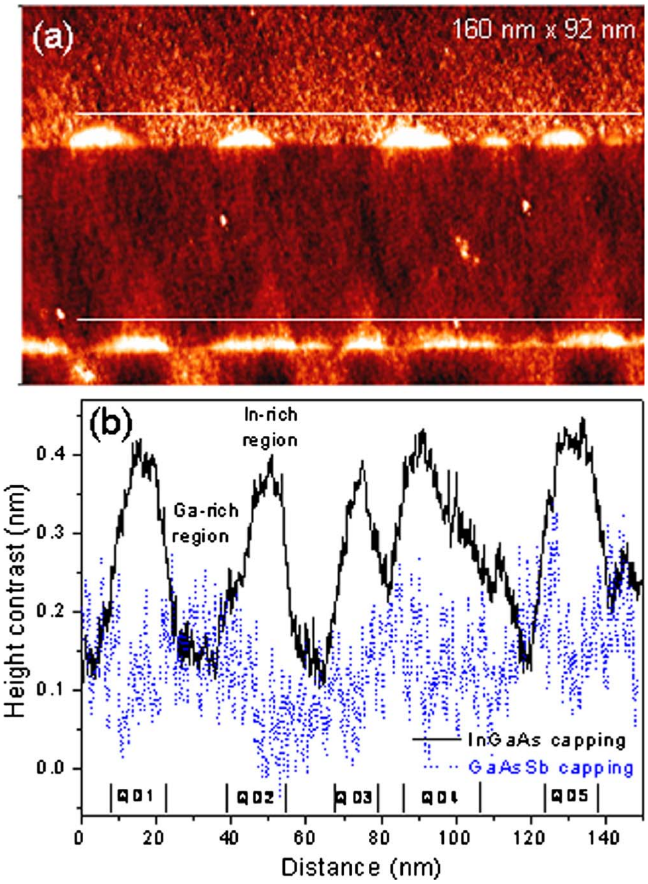

FIG. 1. (Color online) (a) Filled states image of the two InAs QD layers $(V=-1\ \text{V})$. (b) Height line profiles along the two lines shown in Fig. 1(a). The two profiles are shifted for clarity. The position of the QDs in the InGaAs-capped layer is indicated in the horizontal axis. The inhomogeneous contrast in the InGaAs layer indicates composition modulation (the brighter regions are In-rich regions).

while the contrast in the InGaAs capping layer is quite inhomogeneous, showing brighter and darker vertical regions, it is quite homogeneous in the GaAsSb capping layer. This can be much more clearly observed by plotting a line profile of the measured height along both capping layers. Figure 1(b) shows the height profile along the two lines shown in Fig. 1(a), which are located 7.5 nm above the wetting layer. We choose to measure the profiles very close to the QDs because the relevant processes that take place during capping happen during the deposition of the first monolayers (MLs) of material. While in the case of GaAsSb capping layer the profile is quite flat, a strong modulation is present in the case of InGaAs capping layer. The brighter regions are exactly located on top of the QDs, as shown in Fig. 1(b), in which the position of the QDs in the first layer is indicated in the horizontal axis. Under these measurement conditions, In-rich InGaAs appears brighter than Ga rich InGaAs due to both smaller band gap and stronger outward relaxation after cleavage due to higher compressive strain.[15,16] The inhomogeneous In distribution is due to a strain-driven composition modulation in the capping layer (the In adatoms on the growth surface migrate toward the regions on top of the dots to minimize the strain, creating a columnarlike In-rich region above the dots). This effect decreases with the distance to the QDs as the strain field of the QDs does, and the In accumulation becomes negligible at 20–25 nm above the QD layer. This process has been observed before in similar samples,[14] as well as in In(Ga)As/GaAs QDs capped with InGaAs.[17,18] Surprisingly, this composition modulation does not happen in the GaAsSb capping layer, despite the fact that GaAsSb has a much larger miscibility gap than InGaAs, and therefore, a much stronger tendency to phase separation.[19] The reason for this is not clear, although it is probably related to the surfactant effect of Sb, which stabilizes or "freezes" the growth front avoiding the phase separation to happen.

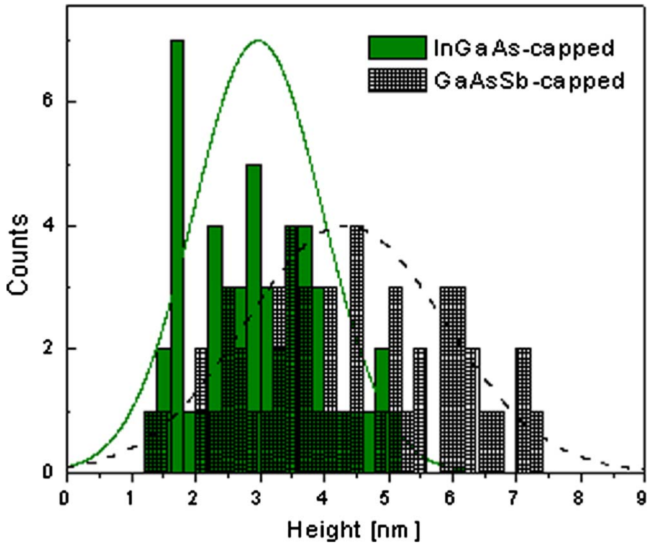

FIG. 2. (Color online) QD height distribution in the two analyzed layers. Both the average and the maximum values are higher for GaAsSb-capped QDs. It must be noticed that the broader distribution in the case of GaAsSb-capped QDs does not mean a stronger size dispersion, is just a consequence of the fact that the QDs are taller.

The slight contrast inhomogeneity observed in the GaAsSb layer, with regions above QDs slightly darker than between QDs, is likely due to the specific scanning conditions. It can happen, for certain gain settings and a high scanning speed, that after a big and abrupt change in the current (like at the interface between a QD and the capping layer) the feedback loop that keeps the current constant cannot immediately reach the stable conditions and a region with reduced brightness appears. This is not observed in the InGaAs layer because it is compensated by the presence of the brighter In-rich InGaAs regions. It must be emphasized that the contrast induced by this effect is negligible compared to the one observed in the InGaAs layer [see Fig. 1(b)].

It can also be observed from Fig. 1(a) that there are differences in the QD size and shape between the two layers. Figure 2 shows the QD height distribution obtained after analyzing approximately 50 QDs in each layer. The average height in the GaAsSb-capped QDs is higher than in the InGaAs-capped QDs (4.3 nm and 3.0 nm, respectively), as shown by the average curves in the image. Moreover, the maximum measured height is 7.4 nm in GaAsSb-capped QDs and only 5.2 nm in the reference layer. If we neglect the size inhomogeneity in the QD ensemble, we can consider that the maximum measured height represents the real QD height. This is due to the fact that, if the QDs are symmetric

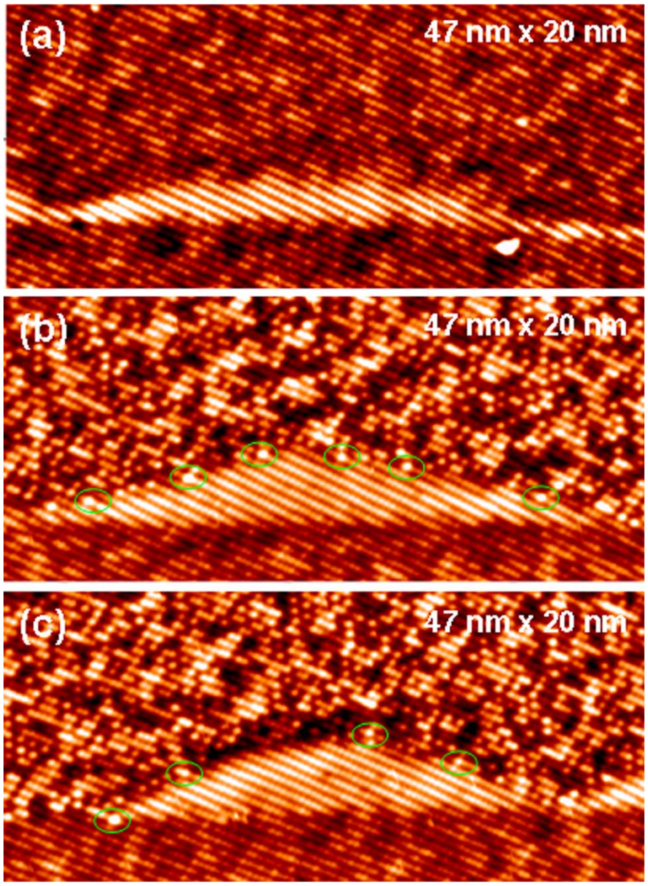

FIG. 3. (Color online) High resolution local mean equalization filtered images of an InGaAs-capped QD (a) and GaAsSb-capped QDs (b) and (c). The circles in (b) and (c) indicate the presence of Sb atoms on (or very close to) the QD surface. The dark spots inside the QDs visible in (c) correspond to individual Ga atoms.

full pyramids (or truncated pyramids), only the QDs cleaved through the middle (or through the flat top facet) show the total height and those cleaved in planes progressively farer from the center appear with progressively smaller heights, giving rise to height distributions as that of Fig. 2.[16] Therefore, it can be concluded that QDs capped with GaAsSb are ~2 nm higher than those capped with InGaAs. Moreover, GaAsSb-capped QDs look like a full pyramid, while QDs capped with InGaAs are clearly truncated pyramids. This can be seen in Fig. 3, in which high resolution images of a QD in the first layer [Fig. 3(a)] and two in the second layer [Figs. 3(b) and 3(c)] are shown. The top of the QDs is quite flat in the case of InGaAs capping but is more pyramidal-like in GaAsSb-capped QDs. Actually, some of the dots capped with GaAsSb are quite symmetric full pyramids [see Fig. 3(b)]. In other cases, the pyramid is more asymmetric and sometimes it shows one extra facet [see Fig. 3(c)].

These differences in height and shape between the two layers must originate from the capping process since the QDs are grown under the same conditions and must be exactly the same before capping. It is well known that QDs can be strongly affected by the capping process, which usually dissolves the top of the dots and decreases their height.[20,21] The differences found in this study indicate that capping with GaAsSb reduces or completely suppresses QD decomposition during capping. This result is in agreement with what was recently observed in GaAsSb-capped InAs QDs grown on GaAs substrates.[12] In that case, it was pointed out that the smaller strain induced in the QDs during capping by GaAsSb compared to GaAs could be the main reason.[12] In the present study both InGaAs and GaAsSb are lattice-matched to InP so there are no differences in the strain. Therefore, the effect of the GaAsSb capping layer cannot be related to strain effects but more to chemical effects. One possible explanation would be that the presence of Sb "freezes" the growth front reducing the mobility of the Ga adatoms, which are forced to stay where they arrive. For that reason, and contrary to what happens with other materials,[22] the capping layer would directly grow on top of the QDs from the beginning, protecting them from intermixing and segregation, the two main factors causing QD decomposition. This explanation is in agreement with the fact that no composition modulation is observed in the GaAsSb capping layer despite the high miscibility gap (as described before), indicating that no adatom migration takes place in the presence of Sb.

One additional point indicating that there is no intermixing during capping with GaAsSb is the fact that there is no Sb inside the QDs. This can be concluded from atomically resolved negative voltage images like those in Fig. 3. A local mean equalization filter was applied to these images in order to enhance atomic details by removing the large scale background contrast. This allows a better differentiation of the Sb and As atoms in the first atomic plane. Due to the different size and bonding configuration, Sb atoms appear much brighter than As atoms (the bright spots in the capping layer of Figs. 3(b) and 3(c) are Sb atoms). After analyzing several height profiles along the atomic rows in the capping layer we obtain an average height contrast between Sb and As atoms in the capping layer of 0.7 Å. On the contrary, the height profiles along atomic rows inside the QDs are much more homogeneous, the height contrast between adjacent atoms being smaller than 0.05 Å. This means that there is probably no Sb inside the QDs. The presence of Sb atoms is only observed in the QD surface planes [see the circles in Figs. 3(b) and 3(c)] but not inside. On the other hand, a few dark spots are observed inside the QDs in the two layers. These dark spots reflect the presence of a small amount of Ga atoms inside the QDs. Although group III elements are not directly observable at negative voltage, what we see is the As atoms affected by the distortion that Ga atoms induce in their surroundings. The amount of Ga is quite small and the QDs are close to 100% InAs. This is confirmed by analyzing positive voltage images (not shown) in which In and Ga are directly imaged.

## IV. CONCLUSIONS

In conclusion, X-STM has been used to study at the atomic scale the effect of a lattice-matched GaAsSb capping layer on the structural properties of self-assembled InAs QDs grown on (311)B InP substrates. The strain induced composition modulation present in the lattice-matched InGaAs capping layer is absent in the GaAsSb capping layer, despite the stronger miscibility gap. GaAsSb-capped QDs are ~2 nm higher than InGaAs-capped ones. Moreover, the shape of GaAsSb-capped QDs looks more similar to a full pyramid while InGaAs-capped QDs are clearly truncated pyramids. This indicates that GaAsSb protects the dots from decomposition during capping. Since both capping layers are lattice matched, the reason for this is not related to the strain but probably to the surfactant effect of Sb.

## ACKNOWLEDGMENTS

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