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Self-assembled quantum dots of InSb grown on InP by atomic layer molecular beam epitaxy: Morphology and strain relaxation

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Self-organized InSb dots grown by atomic layer molecular beam epitaxy on InP substrates have been characterized by atomic force and transmission electron microscopy. Measurement of high-energy electron diffraction during the growth indicates a Stransky–Krastanov growth mode beyond the onset of 1.4 InSb monolayer (ML) deposition. The dots obtained after a total deposition of 5 and 7 ML of InSb present a truncated pyramidal morphology with rectangular base oriented along the $\langle 110 \rangle$ directions, elongated towards the [110] direction with $\{111\}B$ lateral facets, with $\{113\}/\{114\}/\{111\}A$ lateral facets in $[1\bar{1}0]$ views, and (001) flat top surfaces. The mismatch between the dot and the substrate has been accommodated by a network of 90° misfit dislocation at the interface. A corrugation of the InP substrate surrounding the dot has been also observed. © *1996 American Institute of Physics.* [S0003-6951(96)03051-3]

In the past much effort was devoted to the heteroepitaxy of III-V compounds in which the layers were kept below the onset of three dimensional growth to obtain bidimensional quantum wells. Lately the interest has moved towards those systems for which the two-dimensional transition from (2D) to 3D growth mode, depending on the growth conditions, leads to the development of self-organized zero dimensional structures, since this self-organization avoids many technological limitations and this provides the benefits of 3D carrier confinement for optoelectronic devices.[1] In order to obtain an array of isolated quantum dots with uniform distribution that are small enough, III-V systems with relatively high intrinsic strain (f) are used. There are several reports about the growth of quantum dots of $In_xGa_{1-x}As$[2,3] (f up to 7.2%) and $Ga_xIn_{1-x}P$[4] ($f \simeq 4\%$) on GaAs, InAs/InP[5] ($f = 3.2\%$), or InP/GaAs[6] ($f = 3.8\%$), with the aim of increasing the band-gap tailoring and widening the range of emission wavelengths. Nevertheless, despite the promising expectations of the use of InSb as low band-gap material with extremely high electron mobilities for infrared applications, little work has been published on the growth of InSb self-organized low dimensional structures. Most of these studies are limited to the growth of InSb quantum dots on GaAs substrates ($f = 14.6\%$),[7,8] despite the fact that the growth of InSb on InP substrates combines the benefits of emission in the micrometer range and reduced carrier effective masses of high strained materials for high speed devices with a lower intrinsic mismatch (10.4%). Here we extend the scope of self-assembled quantum dot nucleation to the InSb/InP system, by analyzing the growth mode and morphology of self-organized InSb islands by transmission electron microscopy (TEM) and atomic force microscopy (AFM).

InSb was epitaxied on top of an InP buffer of 500 monolayers (ML), both grown at 410 °C on (001) InP substrates by atomic layer molecular beam epitaxy (ALMBE), with a total amount of InSb equivalent to 5 and 7 ML for sample Nos. 5 and 7, respectively. High energy electron diffraction (RHEED) monitoring was used to determine the onset of 3D growth. After growth, the samples were annealed at 440 °C for 120 s. More details about sample growth are reported elsewhere.[10] Specimens were prepared for TEM by mechanical polishing and Ar^+ ion milling bombardment in a cooled stage. Observations were performed along both [110] and $[1\bar{1}0]$ directions in a microscope Philips CM30 operating at 300 kV.

The samples were first examined by AFM to assess the average dot density and the mean size of the dots. AFM images were obtained by a Nanoscope III Multimode AFM Digital Instruments operating in tapping mode. Figure 1, corresponding to sample No. 7, illustrates the main characteristics of the dots. There is a marked anisotropy between the $\langle 110 \rangle$ directions. The dots appear elongated towards the [110] direction, with a mean size of 62 and 90 nm for sample Nos. 5 and 7, whereas the mean size along $[1\bar{1}0]$ is 27 and 33 nm for sample Nos. 5 and 7, respectively. The average density of quantum dots is 8.8×10^9 cm^{-2} for sample No. 5 and 5.5×10^9 cm^{-2} for sample No. 7. The height at half-base width has been estimated at around 14.5 nm and 18 nm for sample Nos. 5 and 7, respectively. Therefore, the size and height of the dots increases as the total amount of InSb deposited rises, whereas the density of dots decreases. This unexpected result can be explained by taking into account the possible coalescence of isolated islands as the number of monolayers is increased. This coalescence is also indicated by the fact that the coverage of the surface of sample No. 5 seems more regular than in sample No. 7 and dots appear fairly well aligned along the $\langle 110 \rangle$ axes with a dispersion of the mean size of the dots along [110] of $\simeq \pm 14$ nm. Conversely, the surface of sample No. 7 exhibits bigger and more elongated dots with a higher size spread of $\simeq 16$ nm, and the alignment of the dots along the direction perpendicular to their elongation is reduced. Similar results have been

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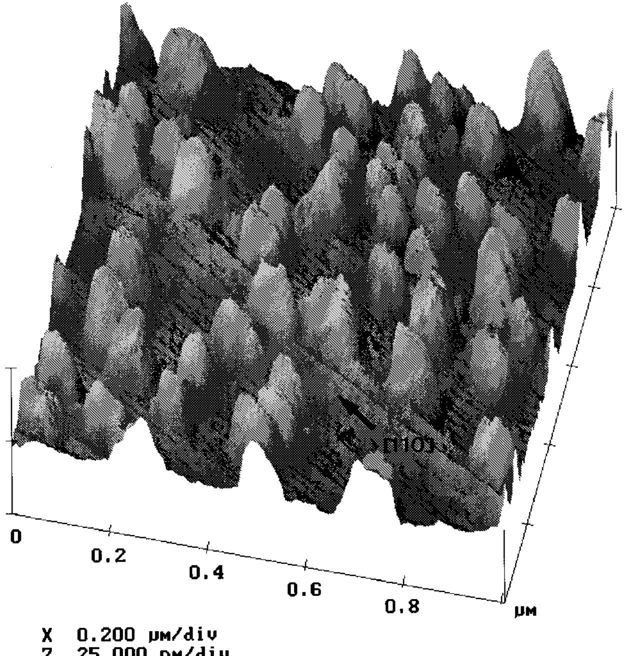
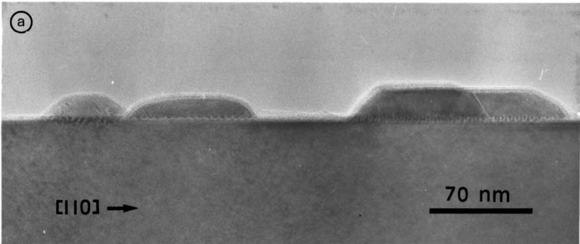


FIG. 1. AFM image of the sample No. 7 exhibiting dot elongation towards the direction [110], dot alignment close to the ⟨110⟩ directions, and surface undulation along the [1$\bar{1}$0] direction.

reported by Moison *et al.*[2] for the growth of InAs dots on GaAs, for which the onset of island coalescence was found to occur beyond the deposition of an equivalent amount of 3 ML of InAs. For InSb dots on GaAs, Bennet *et al.*[8] have found the value of 3.5 ML of InSb before island coalescence, with quite good agreement in dot size and density with our results. In our case, from the clear anisotropy of InSb quantum dots in sample No. 5, we could expect that the island coalescence had taken place before the deposition of the 5 ML. However, the influence of the annealing treatment after growth on the reorganization of initial islands cannot be ruled out, since other authors have demonstrated the influence of growth interruption on the reorganization of InP/GaInP[4] and InAs/GaAs[10] islands due to surface diffusion processes. Finally, we would like to point out another remarkable feature observed in AFM images. In Fig. 1, we can distinguish an anisotropic surface roughness with undulations perpendicular to the direction of dot elongation, whose valleys and hillocks extend nearly coherently across all the layer surface. We will discuss the origin of such undulation.

A second point of interest is the surface dot morphology, as seen by cross-section transmission electron microscopy (XTEM) observation of the dots along the [110] and [1$\bar{1}$0] directions (Fig. 2). Figures 2(a) and 2(b) correspond to sample No. 7 and illustrate the main characteristics commented on, namely, the strong asymmetry of dot size between the ⟨110⟩ directions and the anisotropic surface roughness clearly seen in [110] cross-section views parallel to the dot elongation [Fig. 2(b)]. Similar sample morphology was obtained for sample No. 5 shown in Fig. 2(c). Moreover, in these images we can distinguish the development of lateral facets in InSb dots, and the presence of a flat (001) top surface. In summary, the dots have a truncated pyramidal morphology with rectangular base oriented along the ⟨110⟩ directions, and different lateral facetting depending on the ⟨110⟩ XTEM view.



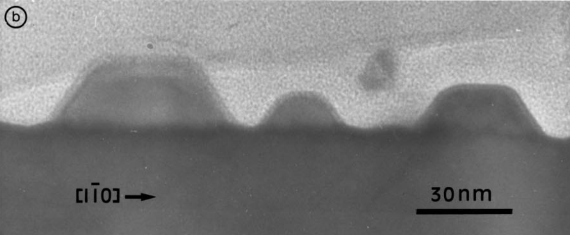


FIG. 2. XTEM images obtained in bright field conditions: (a) [1$\bar{1}$0] view of sample No. 7, revealing dot enlargement along the direction [110]. (b) [110] view of sample No. 7, exhibiting surface undulation in the direction perpendicular to the dot elongation. (c) [110] view of sample No. 5, for which the undulation is also evident. Remark the differences in size dispersion between samples Nos. 5 and 7, and the InSb dot facetting.

We completed the structural characterization of the samples by high-resolution TEM (HRTEM) in order to corroborate the nature of lateral facets and to assess the state of strain relaxation of the InSb dots and the type of defects inside them. HRTEM images of sample Nos. 5 and 7 are presented in Figs. 3(a) and 3(b), respectively. The preferential development of {111} lateral facets and (001) top surface was confirmed. As far as the [110] view is concerned the dots exhibit well defined {111}*B* facets. However, although mainly {111}*A* type, {113} and {114} lateral facets are also present in [1$\bar{1}$0] views. Furthermore we noticed the presence of an array of 90° misfit dislocations at the interface between InSb and InP, separated by a mean distance of 45 Å [Fig. 3(a)]. This value is very close to the distance between dislocations expected for a complete strain relaxation by means of Lomer dislocations (around 44 Å). Moreover, the selected area diffraction pattern (inset in Fig. 3) exhibits splitting of the diffraction spots due to the large difference in layer parameter between the InSb and the InP, in agreement with a total strain relaxation. Several mechanisms have been suggested to explain the nucleation of such dislocations in three dimensional islands.[11,12] Recently, Chen *et al.*[13] have proposed one to account for the formation of 90° type misfit dislocation based upon the nucleation of a Frank partial dis-

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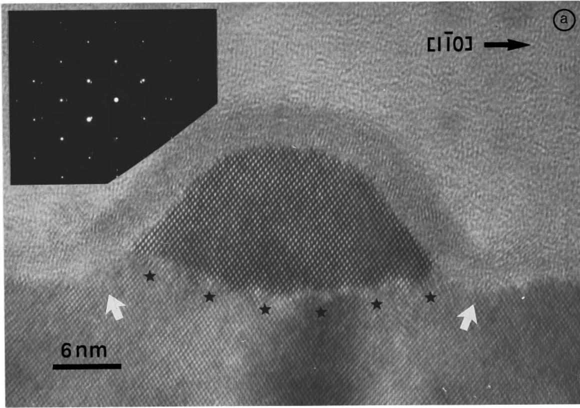

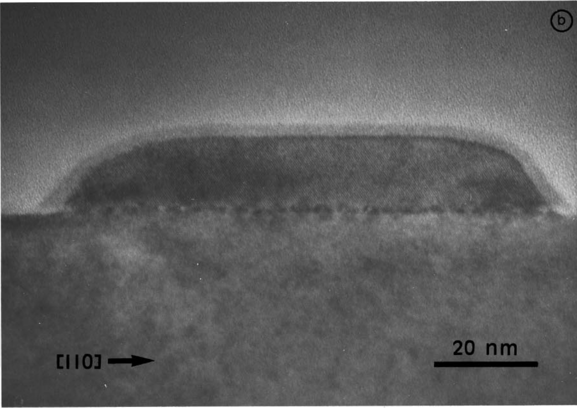

FIG. 3. High resolution [110] Tem images: (a) sample No. 5 and (b) sample No. 7, exhibiting the preferential {111} lateral facets and (100) top surfaces and the network of misfit dislocations at the interface. The inset in (a) shows the selected area diffraction pattern whose splitting of the diffraction spots agrees with a total relaxation of the strain.

location at the edges of the dot followed by a stacking fault extended during the growth of the island up to the nucleation of the Shockley partial whose interaction with the Frank one would annihilate the staking fault and give rise to the Lomer dislocation at the interface. This mechanism would explain the frequent presence of stacking faults and microtwins in 3D islands of highly strained materials.

The last point to be addressed is to establish whether the growth of the islands has followed a Stransky–Krastanov mode (change from 2 D to 3D growth mode beyond the deposition of a critical number of monolayers) or a Wolber–Weber mode (with a direct nucleation of InSb islands on top of the InP ALMBE buffer layer). This onset of growth mode transition is strongly dependent on the system mismatch and growth conditions. Hence, whereas a limit of $\simeq$1.7 ML of InAs is usually reported[1,2] for 2D$\rightarrow$3D transition when grown on GaAs or 2 ML for InP on GaAs,[4] for highly strained systems as InSb on GaAs the growth proceeds directly in a 3D way.[7] In our case, the HRTEM images do not show any evidence of the presence of a InSb wetting layer prior to dot formation, and therefore one could expect that the growth also followed a Wolber–Weber mode due to the relatively high strain between InSb and InP. Nevertheless, the RHEED monitorization during growth exhibited a spotty pattern beyond the onset of 1.4 ML of InSb deposition,[9] indicating then, a Stransky–Krastanov growth mode. Thus, it is envisaged that the annealing treatment carried out to favor the island nucleation gave rise to an atomic reorganization eliminating the wetting layer, increasing the island size, and favoring island coalescence. Finally, HRTEM images reveal a fairly good correlation between the surface undulation and the location of the dots [white arrows in Fig. 3(a)]. Consequently, it is likely that the undulation of the substrate appears as a mechanism of strain accommodation which reduces the total surface energy.

In summary, InSb dots self-organized after the deposition of 5 and 7 ML of InSb on InP have been characterized by AFM and TEM. Almost all dots present a similar size and shape with a greater size dispersion as the total amount of InSb increases, whereas the dot density decreases due to island coalescence. The dots present a truncated pyramidal morphology with rectangular base oriented along the ⟨110⟩ directions elongated towards the [110] direction, with {111}*B* lateral facets in [110] views, mainly {111}*A* but also {113}/{114} lateral facets in [1$\bar{1}$0] views, and (001) top surfaces. The mismatch between the dot and the substrate has been accommodated by a network of 90° misfit dislocation at the interface. A corrugation of the InP substrate around the dots has also been observed.

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