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On the optical properties of InAs/InP systems: The role of two-dimensional structures and three-dimensional islands

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We investigate the effects of the interface morphology on the electronic properties of InAs/In systems using in-air atomic force microscopy and low temperature photoluminescence. Atomic force microscopy results show that the distribution of InAs strained film into three-dimensional islands and the two-dimensional wetting layer—typical of the Stranski–Krastanov growth mode—is strongly affected by the characteristics of the substrate and by the morphology of the InP buffer layer. The differences in the optical data are correlated to the different interface characteristics observed by atomic force microscopy. We discuss the origin of emission peaks taking into account the diffusion process of adsorbed atoms on the different types of surface. © *1998 American Institute of Physics.* [S0003-6951(98)00909-7]

The electronic properties of systems with dimensionality lower than two have been intensively investigated theoretically and experimentally in the latest years. The most promising method to achieve zero-dimensional structures has been considered to be the self-organization of strained semiconductor films obtained by atomic layer deposition techniques. Understanding and controlling the processes involved in the formation and evolution of these structures is extremely important to allow a precise description of the systems being studied.

The roughening of heavily strained films on heterointerfaces as a result of the partial relaxation of elastic strain is known to take place at the early stages of film deposition. For most of the systems this phenomenon occurs in the Stranski–Krastanov growth mode[1] which produces systems where three-dimensional islands coexist with the essentially two-dimensional wetting layer. Optical investigations have been used to investigate the electronic properties of several systems containing this type of structure.[2] Surface and interface analysis techniques have provided means to take a closer look at their most important features and have been extremely helpful in the elucidation of the origin of some observations from the optical data. The determination of the way atoms distribute themselves at the initial stages of film deposition provides, for example, consistent means to identify the main contributions for emission spectra from structures based on this type of system.

Atomic force microscopy (AFM) studies of interfaces on strained systems have shown that the characteristics of the surface, where the initial stages of the heteroepitaxy take place, strongly affects the spatial distribution of the strained film. In the case of InAs/InP interfaces, step edges on misoriented substrates and surface corrugations were observed to favor early nucleation of InAs films even at low growth temperature.[3]

In this letter we report on the dependence of the optical properties of InAs/InP structures on the characteristics of the substrates and of the surface that precedes the InAs film deposition. We show that the presence of step edges and/or corrugations on the surface affects the formation of three-dimensional islands and also the two-dimensional film that is deposited among them. We discuss these effects in terms of the diffusion and distribution of surface atoms, during and after film deposition and correlate them with the photoluminescence (PL) results.

The samples studied in this work were grown by chemical beam epitaxy using trimethylindium diluted with hydrogen carrier gas as the group III source and thermally decomposed pure arsine (AsH_3) and phosphine (PH_3) as group V sources. They consist of 300 nm of InP buffer layer with 3*s* InAs deposited on the top and were grown simultaneously on (100) InP substrates nominally oriented and 2° off towards [011] (A surface) and [0$\bar{1}$1] (B surface). Two sets of samples were obtained with respect to the characteristics of the buffer layer. In one of them the growth conditions were chosen to guarantee a smooth InP surface, while the other was grown in kinetically limited conditions described elsewhere so as to obtain a layer with multiterrace periodical structures.[4] The substrate temperature was monitored by infrared pyrometry. The InAs growth rate was 0.7 monolayer/s (ML/s).

We have shown that, during the cooling of the samples, after InAs deposition, the departure from growth temperature (500 °C) is sufficient to modify the characteristics of the film.[5] In this sense a special procedure was used during the cool down. It consists in beginning the cooling of the sample after the InAs deposition and switching the AsH_3 flux to PH_3 after different time intervals, Δt, to grow a thin InP layer on the top of the InAs film. By depositing this InP cap layer, the InAs distribution on the surface is interrupted at different stages of the cooling process, enabling the evaluation of the surface evolution[5] and the achievement of a more realistic picture of the interfaces in structures we used for optical investigation. The thickness of the InP cap layer was either very thin (1–2 ML), to allow observation of the interface by in-air AFM, or 35 nm-thick, for the PL experiments. The PL measurements were performed with the samples immersed in superfluid He using the 4880 Å line of an Ar^+ laser as excitation source. Power densities of 10 mW/cm^2 and lower were

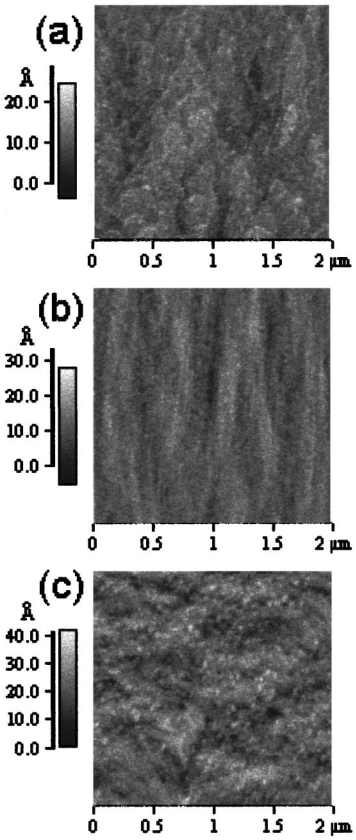

FIG. 1. In-air AFM images of 2 ML InAs film deposited on different types of substrates and on smooth InP buffer layer. (a) Nominally oriented (100) substrate, (b) A-surface, and (c) B-surface, respectively. The scanned area was 2×2 μm^2.

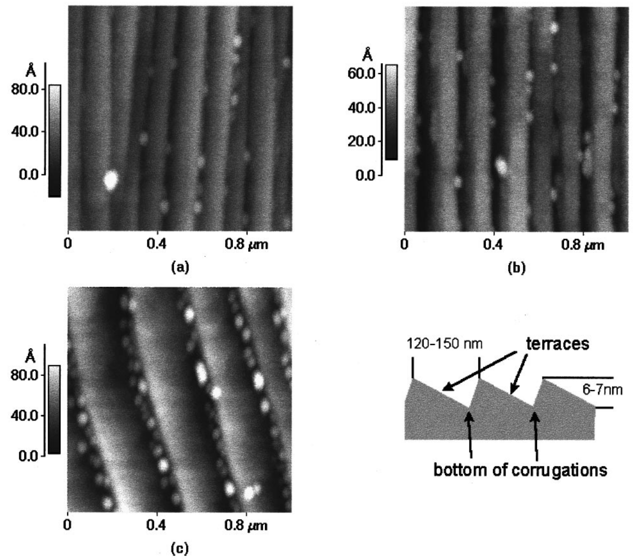

FIG. 2. In-air AFM images of 2 ML InAs film deposited on different types of substrates and on InP buffer layer with multiterrace periodical structure. (a) Nominally oriented (100) substrate, (b) A-surface, and (c) B-surface, respectively. A schematic view of the cross section of the multiterrace periodic structure used as buffer layer is also shown. The scanned area was 1×1 μm^2.

used to achieve minimum diffusion of photogenerated carriers. The emission spectra were analyzed with a 0.5 m monochromator and detected by a liquid N_2 cooled Ge photodetector and using standard lock-in techniques.

The AFM images of samples grown with a very thin InP cap layer after the InAs deposition ($\Delta t=45$ s) are shown in Fig. 1. The films were deposited on (a) nominal, (b) A, and (c) B surface, respectively. The terraces observed on the nominal substrate are not seen on the other types of surface due to limitation on the lateral resolution of the AFM. On the films deposited on the nominal substrate and A surface, no three-dimensional island can be observed by in-air AFM. On the other hand, on the B-surface small three-dimensional islands can be distinguished on the surface, as shown at the height scale on the left of the images. This effect is easily noticed for higher values of Δt, for which islands are fully developed.[5]

In a previous work we reported that islands tend to nucleate earlier on surfaces presenting B-steps than on those with A-steps or nominal substrates.[3] This behavior has been explained by the existence of a barrier for adsorbed atoms to move across a step A model proposed by Schwoebel[6] and Swang[7]—which was shown to be more effective for the former type of surface. In addition, the direction along which terraces run in the different types of surface and its relation to the high diffusion direction, namely [011],[8] seem to determine the distribution of the atoms on the surface. Island size, shape, and surface distribution have then been shown to be strongly affected by the step type and step density on the surface. On the B-surface, in which terraces run perpendicularly to the [011] direction, islands are more uniform in size, shape, and are more uniformly distributed on the surface.

In Fig. 2 we show the AFM images of InAs films deposited on corrugated InP for investigation of the effect of this surface morphology on film distribution. In this figure we also show the schematic cross section of the periodical structure used as buffer layer. Three-dimensional islands are observed on all surfaces, preferentially located along the corrugations. The islands on B-surfaces [Fig. 2(c)] are more uniformly distributed along them if compared to the other types of surface.

Figure 3(a) shows the PL spectra for the samples grown on nominally (100) substrate with the different types of buffer layers as indicated in the figure. The structure deposited on the smooth buffer layer present PL spectrum with multiple peaks from 0.9 to 1.25 eV. The occurrence of multiple peaks in the PL spectra of InAs/InP quantum-well (QW) structures has been attributed to the formation of two-dimensional terraces of InAs of different numbers of monolayers. This observation has been related the redistribution of the InAs layer due the interruption between this film deposition and the growth of the InP cap layer. The peaks correspond to QWs between 1 and 3 ML of thickness.[9] For the InAs film deposited on the intentionally corrugated buffer only two peaks at 1.049 and 1.1 eV are observed, indicating two distinct regions of the sample with different thickness. The peak at 1.1 eV has a full width at half maximum of 15 meV, which is relatively low for such a thin well (1–2 ML). This peak, which is attributed to the fundamental transition in the quantum well region formed on the terraces, is about five times more intense than the band at 1.049 eV which is three times broader than the more intense peak. The differences on PL intensity and linewidth can be explained by the

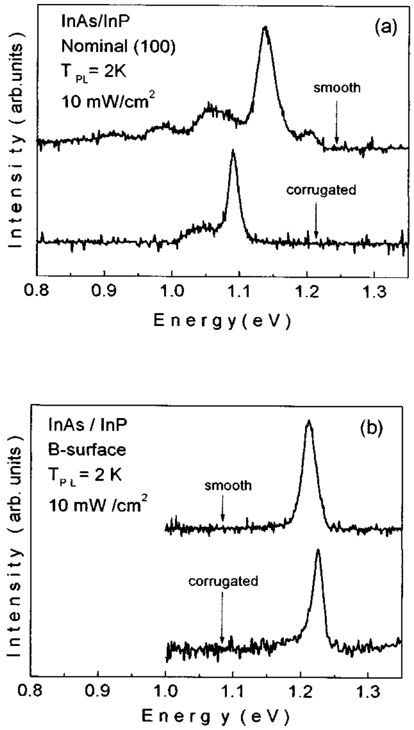

FIG. 3. Low temperature photoluminescence of 2 ML InAs film deposited on (a) nominal (100) and (b) 2° off towards [011] direction (B-surface) InP substrates, respectively. The different morphologies of the InP buffer layer are indicated.

different accumulation rate of material which has been observed to be higher at the bottom of the corrugations than on the regions that separated them.[10] These regions consist of large terraces (120–150 nm of width), corresponding to about 80% of the surface area. The emission from this area is, thus, expected to dominate the spectra. Additionally, the film grown at the bottom of the corrugations tends to be more irregular in thickness, accounting for the broadening of the less intense band. The samples on substrates with A-surface, present a similar behavior to that seen on nominal ones.

The spectra for the structures grown on substrates with B-steps are shown in Fig. 3(b). One peak around 1.2 eV clearly dominates the spectra. The shift to higher energies on the spectra for the corrugated sample suggests that this surface morphology also contributes to increase to the incorporation of the surface atoms, leading to an earlier nucleation of the islands than the smooth one. It is important to remark that the corrugations, on this type of surface, form approximately at 45° from the high diffusion [110] direction, while for A-surface the terraces on the corrugated structure are formed along this direction.[4]

The AFM results on our samples show how the distribution of the InAs film is affected by the morphology of surface underneath and the PL results suggest that the structures based on this film are also strongly dependent on its characteristics. The more the surface morphology favors the formation of three-dimensional structures at the early stages of InAs deposition, the less material is left to form the wetting layer. For samples grown on either type of buffer layer deposited on B-surface, the uniformity of the two-dimensional film accounts for the observation of only one peak on the PL spectra. The blue shift of the PL peaks for the sample grown on the surface with the multiterrace periodical structure indicates that this type of morphology contributes to accelerate the formation of three-dimensional islands along the corrugations and consequently generating a thinner wetting layer. The consistent shift of the PL peaks on these samples compared to those grown on the other types of substrate, reinforces the idea that B-steps promote a faster accumulation of InAs at the step edges and induce the formation and increase of three-dimensional structures at these regions. The different behavior observed for structures grown on the nominal substrate on the two different morphologies can be explained by the fact that the formation of the periodic structure is delayed in this type of surface as compared to those on B-surface, therefore being less effective to generate island nucleation.

On the other hand, the PL results for samples grown on smooth buffer on nominal and A-surfaces indicated the formation of quantum well structures with a different number of monolayers, giving rise to a series of emission peaks in the spectra. However, when the buffer layer was corrugated the number and the intensity of PL peaks from these structures decreased as compared to those grown on smooth surfaces. The presence of corrugations on these surfaces seems to be providing regions where the formation of three-dimensional islands is favored. The apparent delay in the formation of three-dimensional structures on these types of surface can be related to the enhancement of the diffusion anisotropy, particularly in the case of A-surface, in which terraces run along the high diffusion direction. The peak that dominates the PL spectra from these samples can therefore be assigned to a more uniform wetting layer.

In conclusion, we have shown that the process involved in the formation of InAs/InP interfaces can be investigated using optical measurements. The correlation between optical and morphological data provides a clear scenario on how InAs film distribution is affected by the characteristics of the InP layer that precedes InAs deposition and its effect on the resulting structures.

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[1] R. Nötzel, Semicond. Sci. Technol. **11**, 1365 (1996), and references therein.
[2] K. Kash, J. Lumin. **46**, 69 (1990), and references therein.
[3] M. A. Cotta, C. A. C. Mendonça, E. A. Meneses, and M. M. G. Carvalho, Surf. Sci. **338**, 84 (1997).
[4] M. A. Cotta, R. A. Hamm, T. W. Staley, S. N. G. Chu, R. Hull, L. R. Harriot, M. B. Panish, and H. Temkin, Phys. Rev. Lett. **70**, 4106 (1993).
[5] C. A. C. Mendonça, M. A. Cotta, E. A. Meneses, and M. M. G. Carvalho (unpublished).
[6] R. L. Schoebel and E. J. Shipsey, J. Appl. Phys. **37**, 3682 (1966).
[7] S. C. Wang and G. Erlich, Phys. Rev. Lett. **67**, 2509 (1991).
[8] K. Ohta, T. Kojima, and T. Nakagawa, J. Cryst. Growth **95**, 71 (1989).
[9] J. F. Carlin, R. Houdré, A. Rudra, and M. Ilegens, Appl. Phys. Lett. **59**, 3018 (1991).
[10] M. A. Cotta, R. A. Hamm, S. N. G. Chu, L. R. Harriot, and H. Temkin, J. Appl. Phys. **75**, 630 (1994).