**In situ** measurements of InAs and InP (001) surface stress changes induced by surface reconstruction transitions

David Fuster*, María Ujué González, Yolanda González, Luisa González

Instituto de Microelectrónica de Madrid (CNM-CSIC), Isaac Newton 8, 28760 Tres Cantos, Madrid, Spain.

**Abstract**

The anisotropic surface stress changes associated with the transition between different surface reconstructions of InAs and InP (001) surfaces are measured *in situ* and in real time in a molecular beam epitaxy (MBE) system. Reflectivity anisotropy of the surface measured at 1.96 eV, together with reflection high energy electron diffraction (RHEED) pattern, are used in order to identify the surface reconstructions, and the monitoring of the substrate curvature evolution to determine the variations in surface stress. Our results show the important contribution to the surface stress of the dimers present in these reconstructed surfaces. Furthermore, we provide for the first time quantitative values of the surface stress changes due to the transition between surface reconstructions for these III-V semiconductors compounds. We obtain values for these changes up to 0.7 Nm⁻¹, that is, of the same magnitude as the stress induced by deposition of one monolayer during growth of lattice-mismatched III-V semiconductor heteroepitaxial systems. This points out the great importance of surface stress evolution in this kind of processes.

**Keywords:** Surface reconstructions, indium arsenide, indium phosphide, surface stress, molecular beam epitaxy.

* Electronic mail: davidf@imm.cnm.csic.es
1. Introduction

Surface and interface stress, together with surface and interface energy, are important thermodynamic quantities which have a determinant influence on the growth mode, abruptness of the interface, critical thickness for relaxation, shape transitions and other related processes occurring during heteroepitaxial growth [1-3]. The surface stress, $\tau_s$, is defined as the reversible work per unit area needed to elastically stretch a pre-existing surface ($\tau_s$ is therefore measured in units of force per unit length, Nm$^{-1}$), and hence it can be understood as the force per unit length exerted by a surface during elastic deformation. In this way, it is clear that surface and interface stress have a decisive influence on the critical thickness in pseudomorphic growth of lattice-mismatched heteroepitaxial systems: depending on the relative sign of misfit and surface/interface stress, this last one can lead to the stabilization or destabilization of the deposited epilayer. Moreover, ab-initio calculations estimate the order of magnitude of surface stress around 1 Nm$^{-1}$ [3]. This is the same order of magnitude of the misfit stress accumulated during the growth of a few monolayers in low mismatch III-V semiconductors heteroepitaxy [4] or involved in the self-assembling of semiconductor nanostructures such as quantum dots or quantum wires [5-8], which gives an idea of the importance of the surface stress in these highly interesting technological processes.

Surface stress arises from the charge redistribution in the surface bonds due to the absence of atoms above the surface [1]. This charge redistribution often implies a rearrangement of the surface atoms, generating either compressive (if the surface would like to expand under its own stress, defined as negative) or tensile (if the surface would like to contract under its own stress, positive) stress. In the case of III-V semiconductors, at growth conditions the surfaces are often reconstructed, showing different reconstructions as a function of pressure and substrate temperature. Owing to the particular atomic arrangement, each surface reconstruction will present a different surface stress. Furthermore, the reconstructed surfaces are frequently asymmetric, in such a way that the associated surface stress is anisotropic in those cases.

Being the realization of experiments to obtain absolute values of surface stress with a good accuracy not possible, several techniques have been developed with the purpose of measure the changes of $\tau_s$ associated with different processes, such as adsorption on a clean surface, epitaxial
growth or surface reconstructions transitions [1-3]. In particular, the changes in surface stress can be measured *in situ* and in real time by monitoring the variations they induce in the curvature of the substrate through the deflection of two parallel laser beams reflected at the substrate surface. Via this technique, the variations in surface stress caused by changes in surface reconstructions have been demonstrated in metals [Au (001), Au (111)] [1] and GaAs (001) surfaces [9].

Using this approach, in this work we study the variation in the surface stress produced by the change of surface reconstruction on the (001) surfaces of InAs and InP. Even though surface stress constitutes an important issue in semiconductors heteroepitaxy, as mentioned above, to our knowledge there are no experimental quantitative data on this magnitude for III-V semiconductors so far. Thus, it is the purpose of this paper to quantify the changes in the surface stress along the two principal directions, [110] and [011], caused by the transition between different (001) surface reconstructions in the InAs and InP compounds. The results shown here are valuable data to get a better understanding of the different stress contributions (surface stress and mismatch) during growth of heteroepitaxial systems involving any of these compounds.

The paper is organized as follows. The next section describes the experimental techniques used to identify the different surface reconstructions and to measure the changes in surface stress, $\Delta \tau_s$. Some experimental considerations regarding the relationship between the detected substrate bending and the calculated $\tau_s$ are also provided in this section. In the results section, after a brief overview of the considered InAs and InP (001) surface reconstructions and the expected contributions to surface stress, the measurements performed for each compound are shown and the quantitative values for the surface stress changes induced by the surface reconstructions transitions are provided. Finally, several considerations of the implications that these values of $\Delta \tau_s$ have for heteroepitaxial growth are discussed.

2. Experimental

In this work, we have measured the variations in surface stress associated with the transitions between the typical InAs and InP (001) surface reconstructions occurring at current molecular beam epitaxy growth conditions. In order to identify unambiguously the considered surface reconstructions, we have performed reflectivity anisotropy (RA) experiments in combination with
reflection high energy electron diffraction (RHEED) on standard (001) substrates. RA measurements are highly sensitive to the surface structure, surface chemistry, and surface stress [10-12], and allow identifying the different surface reconstructions with otherwise identical unit cell dimensions, which are not easily discriminated by RHEED. The RA experiments have been made using a He-Ne laser with $\lambda = 1.96$ eV, and have consisted of the monitorization of the RA signal under an established substrate temperature and sequence of III- and V- group element fluxes (the RHEED pattern was also recorded during the whole process).

The surface stress changes between the different reconstructions have been measured in a parallel experiment, at the same substrate temperatures, and following an identical sequence for fluxes than in the RA and RHEED experiments. For the measurements of surface stress evolution, we use the experimental setup sketched in Figure 1. We have employed elongated cantilever-shaped thin InP and GaAs (001) substrates, as shown in the figure, whose thickness, $h_s$, is around 150 $\mu$m. The substrates are cleaved in such a way that the long axis of the cantilever corresponds to either [110] or [011] direction, and the experiments have been carried out in both directions since $\tau_s$ is expected to be anisotropic in reconstructed surfaces. The samples have been mounted using a molybdenum clip on a conventional substrate holder with a hole at its centre so that heating of the cantilever is provided by direct backside radiation. After standard oxide desorption, a buffer layer was grown on the InP (001) cantilevers, and a thick InAs layer on the GaAs (001) ones, in order to provide reproducible and well characterized InP and InAs (001) surfaces.

The molybdenum clip holds the cantilever by an end, as can be seen in the figure, the other end being allowed to bend freely. An optical method, similar to that used in several previous works to measure the surface stress and the accumulated stress during heteroepitaxial growth processes [1-9], has been implemented to detect the substrate bending. In our case, two parallel laser beams are reflected on the sample surface towards two split photodiodes (see figure 1). One beam (the reference) is reflected on the fixed substrate end, and the other beam (the signal) is reflected on the free to bend cantilever end. The use of two beams is necessary in order to provide compensation for thermal or mechanical drifts. The deflection of the laser beams, $\Delta x_{\text{ref}}$ and $\Delta x_s$, provides the evolution of the curvature of the cantilever, $\Delta(1/R)$, through the simple geometrical relation:
\[
\Delta \left( \frac{1}{R} \right) = \frac{\Delta x_{\text{ref}} - \Delta x_s}{2Ld},
\]

where \( L \) is the distance between the substrate and the photodiodes, and \( d \) is the distance between the two incident spots on the sample surface. The surface stress changes originating this substrate curvature are then obtained by means of the well-known Stoney’s equation [1, 13]:

\[
\Delta \tau_s = \frac{M_s h^2}{6} \Delta \left( \frac{1}{R} \right),
\]

with \( M_s \) the biaxial modulus of the substrate, defined as \( M_s = \frac{Y_s}{1 - \nu_s} = c_{11} + c_{12} - 2c_{12}^2/c_{11}, \)

\( Y_s \) being the Young’s modulus of the substrate, \( \nu_s \) its Poisson’s ratio and \( c_{ij} \) the corresponding elastic constants. To calculate the biaxial modulus of the III-V semiconductors considered in this work, InAs and InP, we have used the data for the elastic constants given in Ref. [14], which provide the following values: \( M_s \) (InAs) = \( 79 \times 10^9 \) Pa, \( M_s \) (InP) = \( 95 \times 10^9 \) Pa and \( M_s \) (GaAs) = \( 123 \times 10^9 \) Pa.

The former version of Stoney’s equation corresponds to the case of biaxial isotropic stress and free two-dimensional bending of the substrate and, strictly speaking, this is not our experimental configuration. Due to the clip holding the cantilever, the bending in the short axis is restricted. However, previous works [1] have demonstrated that, while keeping a relationship between both lateral dimensions such as \( b \geq 3a \) (see Fig. 1 for lateral dimensions definition), the transversal strain does not influence the bending along the long axis and the assumption of free two-dimensional bending is reasonable. In our case, the lateral dimensions, \( a \times b \), of the cantilever substrates employed were 3 \( \times \) 12 mm - 3 \( \times \) 15 mm, assuring largely the mentioned relationship. Regarding the stress isotropy, we have already mentioned that the surface stress is expected to be anisotropic in reconstructed surfaces, and it could even be uniaxial. When considering anisotropic stress, it should be taken into account that both the curvature along the considered direction and that along the perpendicular one contribute to the stress component along the substrate long axis [15]. The correct expression of Stoney’s equation in this case, for surface stress along the directions considered in this work, [110] or [1 \( \overline{1} \) 0] (the main directions for III-V semiconductors in (001) surfaces), is:

\[
\Delta \tau_s(i) = \frac{M_s + 2c_{44}}{2} \left( \frac{1}{R(i)} \right) + \frac{M_s - 2c_{44}}{M_s + 2c_{44}} \Delta \left( \frac{1}{R(j)} \right) \quad \text{for } i,j = [110], [1 \overline{1} 0]
\]
For purely uniaxial stress (again along [110] or [0 1 1] directions) this expression reduces to:

\[ \Delta \tau_s = \frac{4M_s c_{44}}{M_s + 2c_{44}} \frac{h^2}{6} \Delta \left( \frac{1}{R} \right). \]  

(4).

Since in the considered materials the elastic constant \( c_{44} \) is approximately \( M_s/2 \) (\( c_{44} \) (InAs) = 39.5\times10^9 \text{ Pa}, \( c_{44} \) (InP) = 45.5\times10^9 \text{ Pa} and \( c_{44} \) (GaAs) = 59\times10^9 \text{ Pa}), in all cases the error done by using Eq. (2) instead of the correct Eq. (3) and (4) is lower than 2\%, which is smaller than the experimental uncertainties in determining the geometrical parameters of the setup, therefore justifying the use of Eq. (2) in our case.

3. Results

The (001) reconstructed surfaces of the III-V semiconductor compounds consist of periodic arrays of III- or V- group element dimers. On Figure 2 we show the so far proposed atomic models for the surfaces studied here: the InP (001) and InAs (001) surface reconstructions present at temperatures above 380 °C [16, 17]. In the figure, the surface reconstructions are ordered by decreasing amount of V-group element covering the surface, indicated in monolayers (ML). The atoms involved in the surface dimers are closer to each other than the equivalent atoms in the bulk lattice, and therefore the bonds associated with the dimers are stretched. This induces a tensile, or positive, surface stress along the direction of the dimers: it is easy to see that in this situation the surface would like to contract under its own stress. Therefore it can be intuitively understood that, in the case of III-V semiconductors (001) reconstructed surfaces, the amount of surface stress, \( \tau_s \), along the different surface directions will depend on the amount, type and distribution of dimers characteristic of the considered reconstruction. Moreover, since the dimers distribution and amount is different along the different surface directions, the surface stress will be anisotropic. It should be noticed here that there is an important difference regarding the dimers distribution in the (001) surfaces between the III-V compound semiconductors with zincblende structure, such as InAs, InP or GaAs, and those of group IV with diamond structure, such as Si and Ge. In both cases, the surface will consist of terraces separated by steps. However, these steps are monoatomic for Si or Ge (001), since the crystal is monoatomic, in such a way that the dangling bonds, and therefore the dimers, rotate 90° from terrace to terrace. In this way, the surface is comprised of domains of
perpendicularly oriented dimers, and although the surface stress will be locally anisotropic, related to the orientation of the dimers for each domain, the total surface stress will be an average over all the domains and can become even isotropic. In the case of the III-V semiconductors, on the other hand, the steps are biatomic, provoking two rotations of 90°, and thus the dimers do not rotate from one terrace to the next one and they will be all aligned in the same direction, contributing to the total surface stress in the same way.

When the surface undergoes a reconstruction transition, this implies a change in the dimers population and therefore in the associated surface stress which provokes the bending of the thin cantilever. Figure 3 shows schematically the curvature changes induced by the variations in the amount of dimers aligned in the long direction of the cantilever.

Next we show the surface stress changes associated with the transitions between surface reconstructions for InAs(001) in the first place, and InP (001) after that, as determined from the monitorization of the cantilever shaped substrate bending. Measurements have been performed along [110] and [1 T 0] directions, the main directions in (001) surfaces, where the surface dimers are aligned.

3.1. InAs(001)

For this compound, the experiments have been carried out at substrate temperature $T_s=380^\circ$ C and arsenic beam equivalent pressure BEP ($As_4$) = $1.75\times10^{-5}$ mbar. We have followed the same time sequence of the cell shutters in the two kinds of experiments: determination of changes of surface stress along both [110] and [1 T 0], and RA. Figure 4 shows, from bottom to top, the real time evolution of [1 T 0] surface stress, the RA signal, and the changes in [110] surface stress. The sequence of fluxes of the different elements is indicated by the corresponding bar (black for In, and grey for As) between the graphs. Starting from an initial situation where the surface is exposed to no flux, the As cell is opened from $t = 0$ and during 15 seconds; then, between $t = 25$ and $t = 50$ seconds, the In cell is opened, and finally at $t = 62$ s the As cell is opened again. An indium amount of 2.5 monolayers (ML) was deposited during the interval of In cell shutter ON at a rate of 0.1 ML/s. The noise of the surface stress measurements is due to the system vibrations; for search of clarity, a smoothed curve is superposed to the experimental data.
In order to identify the surface reconstructions from the RA signal, we have compared our data taken at fixed wavelength (1.96 eV) with the signal changes obtained for this wavelength in the RA spectra calculated by Ozanyan et al. [18]. Accordingly, the maximum RA signal corresponds to the $\beta$ (2x4) reconstruction and the minimum to the In-rich (4x2), this last reconstruction being clearly detected by observing the RHEED pattern. When the As cell is opened at this temperature (380 °C), the RA signal evolves to a constant value at intermediate levels, which allows us to detect the presence of a $\gamma$ (2x4) reconstruction. The opening of the In cell produces the dropping of the RA signal with an abrupt slope until the (4x2) reconstruction appears in the RHEED diagram. We have assigned the (4x2) level at this point because the evolution of the RA signal from this point on (while In cell remains opened) depends on the surface step structure (previous history of the sample) as has been reported before for GaAs (001) surfaces [19], and does not correspond to surface reconstruction changes. The RA signal level associated to $\beta$ (2x4), $\gamma$ (2x4), and (4x2) surface reconstructions are indicated by horizontal dash-dot lines with the corresponding label in Fig. 4.

In order to evaluate the surface stress variations associated with changes in surface reconstructions we will only consider the stages in which the surface present a unique reconstruction. In particular, the InAs(001) surface presents a $\beta$ (2x4) reconstruction for $t < 0$ s and at $t = 27$ s, a (4x2) reconstruction in the time interval of 30 – 62 s and a $\gamma$ (2x4) reconstruction from 62 s to the end of the experiments, as we have obtained from our RA results.

Once established the intervals of existence of the different reconstructions, we can quantify the changes in surface stress. For the surface stress evolution experiments, we define the zero stress level in each direction as the stress corresponding to the surface reconstruction showing no dimers along the specific direction. Under this criterion, it can be seen that the presence of dimers in each specific direction contributes to the surface stress with a positive increment as corresponds to the tensile character of the stress they generate. In this way, for the measurements along [110] direction we set the zero level at the $\beta$ (2x4) reconstruction, occurring at $t < 0$ s and at $t = 27$ s (2 second after the In cell is opened), because in this reconstruction there are not any dimer aligned in this direction (see Fig. 2). Similarly, for measurements along [110] we set the zero stress level at the In-rich (4x2), observed in the time range between 30-62 seconds. Notice that this establishment of the zero
stress level is arbitrary, as we are quantifying relative surface stress changes and not absolute values.

The measured stress levels corresponding to the different reconstructions in the [110] and [1\bar{1}0] directions are indicated by dashed-dot lines and its corresponding labels in Fig. 4 (top and bottom). We can directly obtain from the results shown on Fig. 4 that the \( \tau_s \) change due to the (4x2) to \( \beta \) (2x4) reconstructions transition is \( \Delta \tau_s = -0.4 \text{ Nm}^{-1} \) along [110] direction and \( \Delta \tau_s = 0.4 \text{ Nm}^{-1} \) along [1\bar{1}0] direction. When the surface reconstruction evolves from \( \beta \) (2x4) to \( \gamma \) (2x4), \( \Delta \tau_s \approx 0.1 \text{ Nm}^{-1} \) along [110] and \( \Delta \tau_s = -0.2 \text{ Nm}^{-1} \) along [1\bar{1}0] are measured. Consequently, the changes between the (4x2) and \( \gamma \) (2x4) reconstructions are \(-0.3 \) and \( 0.2 \text{ Nm}^{-1} \) for [110] and [1\bar{1}0], respectively. These surface stress changes are listed in Table I, ordered by increasing arsenic coverage of the surface.

3.2. InP(001)

For InP(001) substrate, the experiments were carried out at \( T_s = 420^\circ \text{C} \), with a phosphorus beam equivalent pressure \( \text{BEP}(P_2)=1.8\times10^{-5} \text{ mbar} \). Figure 5 shows the results of surface stress measurements along the two principal directions and the RA signal versus time. The shutter sequence is indicated, as in Fig. 4, with the bar between graphs (black for indium and grey for phosphorus in this case). Here, starting again with the surface exposed to no flux, the P cell is opened in the range 3-20 seconds, afterwards the In cell is opened in the range 30-55 seconds and finally the P cell is opened again at 60 seconds. With the same growth rate as for InAs experiments, an indium amount of 2.5 ML was deposited in the corresponding time interval. As in the case of the study of InAs surface, we observe by RHEED and by RA the changes of surface reconstruction and we compare the measured RA signal with the results at 1.96 eV obtained in previous RA spectroscopic works [20, 21] with the aim of obtaining the existence intervals of the different surface reconstructions. For InP surface it is not possible to distinguish by RA measurements at 1.96 eV between the (2x1) and \( \beta 2 \) (2x4) reconstructions because the corresponding RA signal level is the same. Fortunately, the simultaneous RHEED have revealed us that the (2x1) reconstruction appears at this temperature (420 °C) when the P cell is opened, and \( \beta 2 \) (2x4) only exists in the fast
transients related with the aperture or closure of this cell. The RA signal shows a slight take off at the end of experiment. This could be due to the formation of some domains of InP (2x2) surface reconstruction, not enough extended yet to be observed by RHEED. When the In cell is opened, the RA signal drops until a minimum level which means that the MD (2x4) reconstruction appears. We can assign the $\alpha$ (2x4) and $\sigma$ (2x4) RA levels by interpolating between (2x1) and MD (2x4) levels accordingly with experimental results previously reported [20, 21]. The RA signal levels associated to (2x1), $\beta_2$ (2x4), $\alpha$ (2x4), $\sigma$ (2x4) and MD (2x4) InP (001) surface reconstructions are indicated by horizontal dash-dot lines with the corresponding label in Fig. 5. We would like to clarify here that, although recent works have questioned the existence of the well-ordered (2x1) surface reconstruction in the InP (001) surface at MBE conditions [22], our RHEED diagram showed a (2x1) pattern at this temperature when the P cell is opened. We cannot assess that the atomic structure of this surface reconstruction is exactly that shown in Fig. 2, and our RA signal, performed at a fixed wavelength, is not enough to conclude if the present reconstruction is that one or another showing the same electron diffraction periodicity. However, our interest here was to identify the presence of changes in the surface reconstruction, which is certain from the change in the RHEED pattern.

In order to evaluate the surface stress variations associated with changes in surface reconstructions, we will only consider the stages in which the surface present a unique reconstruction. In particular, in this series of experiments the InP surface shows a (2x1) reconstruction in the time intervals 5-20 s and from 62 s to the end and MD (2x4) reconstruction in the 32–60 s time interval.

Once established the existence intervals of the different reconstructions we can quantify the changes in surface stress. In this case, the measurements of the surface stress along [110] direction does not show any change following the shutters cell sequence. This result can be understood because of the inexistence of dimers along this direction in any of the gone through surface reconstruction (see Fig.2): the InP (001) surface does not show surface reconstructions equivalent to the In-rich (4x2) or the $\gamma$ (2x4) reconstructions of InAs (001). So, in this case, $\Delta \tau$, have been only detected along [1 $\bar{T}$ 0] direction. Furthermore, we cannot define the zero level for the surface stress measurements at a reconstruction without dimers along [1 $\bar{T}$ 0]. Instead, we will define the zero stress level as that corresponding to the surface reconstruction with less dimers in this direction and
showing a well defined stage from RA measurements: the mixed –dimer MD (2x4). The measured stress levels corresponding to the different reconstructions in the [110] and [1̅0̅1] directions are indicated by dashed-dot lines and their corresponding labels in Fig. 5 (top and bottom).

We can directly obtain from the results shown on Fig. 5 that the stress change from (2x1) to MD (2x4) reconstruction is $-0.7 \text{ Nm}^{-1}$ along [1̅0̅1] direction. The surface stress changes for InP (001) surface reconstructions are listed in Table II.

### 4. Conclusions

In summary, we have measured the surface stress changes along [110] and [1̅0̅1] directions associated with the transition between different surface reconstructions shown by InAs(001) and InP(001) surfaces.

Our results evidence that, in all the cases studied, the surface stress is highly asymmetric and can be related to the contribution of surface dimers (whose distribution, type and number is the distinct characteristic of surface reconstruction). The changes in surface stress due to changes of surface reconstructions can raise values of about 0.7 Nm$^{-1}$. As a comparison, this amounts about 70% of the misfit stress incorporated by the deposition of one monolayer of InAs on InP(001) (3.2% lattice mismatch) [6].

Our results imply that, as a consequence of its order of magnitude, the surface stress induced by surface reconstructions can be determinant in growth processes in strained heteroepitaxial systems like those leading to nanostructures formation by elastic energy relaxation. In fact, these results help to understand for example the influence of surface reconstructions on the growth mode of highly strained InGaAs/GaAs(001), either two dimensional (2D) or 3D [23], or on the shape of the nanostructures in the InAs/InP(001) system. In this last case, one could choose the formation of quantum wires [6] or quantum dots [24] just by compensating the asymmetric accumulated misfit stress (compressive stress) along [110], responsible for InAs/InP quantum wires formation [6], with the tensile surface stress induced in the same direction by the (4x2) InAs surface reconstruction.

**Acknowledgments:**
This work was supported by Spanish MCyT under project No. TIC2002-04096-C03 and by the SANDiE Network of Excellence (Contract No. NMP4-CT-2004-500101 group TEP-0120). D. Fuster thanks the Spanish MCyT for funding.

References


FIGURE CAPTIONS

Fig. 1. Sketch of the experimental setup used for the surface stress evolution measurements.

Fig. 2. Schematic representation of the atomic arrangement for the different surface reconstructions of InP and InAs (001). The coverage of V-group element atoms, expressed in monolayers (ML), is indicated with the corresponding reconstruction. Note that the more In-rich InP surface reconstruction [MD (2x4)] contains In-P mixed dimers along [1 0 1].

Fig. 3. Schematic diagrams of the curvature changes induced in a cantilever shaped thin enough substrate when the surface undergoes different reconstructions. The augmentation in the population of dimers aligned in the long direction of the cantilever results in the shown bending. This is due to the increase of tensile (positive) surface stress caused by the reduced distance between atoms in the dimers compared to bulk.

Fig. 4. Surface stress measurements along [110] (top of the figure) and [1 0 1] (bottom of the figure) directions together with the reflectivity anisotropy (RA) signal measured at 1.96 eV (in the middle). The sequence of the cells opening is indicated in the bar: black for In and grey for As. The corresponding surface reconstruction at each stage, detected by RA, is indicated.

Fig. 5. Surface stress measurements along [110] (top) and [1 0 1] (bottom) directions with the reflectivity anisotropy (RA) signal at 1.96 eV in the middle. The sequence of the cells opening is indicated in the bar: black for In and grey for P. The corresponding surface reconstructions detected by RA are indicated.
TABLES

Table I. Anisotropic surface stress changes ($\Delta \tau_3$) between different InAs (001) surface reconstructions.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \tau_3$ (Nm$^{-1}$)</th>
<th>[110]</th>
<th>[1 1 0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4x2) $\rightarrow$ $\beta$ (2x4)</td>
<td>-0.4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>$\beta$ (2x4) $\rightarrow$ $\gamma$ (2x4)</td>
<td>-0.1</td>
<td>-0.2</td>
<td></td>
</tr>
<tr>
<td>(4x2) $\rightarrow$ $\gamma$ (2x4)</td>
<td>-0.3</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table II. Surface stress changes ($\Delta \tau_3$) along [110] and [1 1 0] directions between different InP (001) surface reconstructions.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \tau_3$ (Nm$^{-1}$)</th>
<th>[110]</th>
<th>[1 1 0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2x1) $\rightarrow$ MD (2x4)</td>
<td>0.0</td>
<td>-0.7</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 2
FIGURE 3
FIGURE 5