GRAZING INCIDENCE DIFFRACTION ANOMALOUS FINE STRUCTURE OF SELF-ASSEMBLED SEMICONDUCTOR NANOSTRUCTURES

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Abstract

We have studied self-organized Quantum Wires of InAs, grown by Molecular Beam Epitaxy onto a InP(001) substrate, by means of Grazing Incidence Diffraction Anomalous Fine Structure (DAFS). The equivalent Quantum Wires thickness is 2.5 monolayers. We measured the (440) and (420) GIDAFS spectra, at the As K-edge, keeping the incidence and exit angles close to the InP critical angle. The analysis of both the smooth and oscillatory contributions of the DAFS spectrum, provide valuable information about composition and strain inside the quantum wires and close to the interface. We also show preliminary results on InAs wires encapsulated by a 40 Å thick InP capping layer, suggesting the DAFS capability of probing different iso-strain regions of the wires.

Keywords: semiconductor Nanostructures, InAs, Quantum Wires, Quantum Dots.
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1. Introduction

The recent advances in semiconductor growth technology have demonstrated that "spontaneous" self-ordering processes can be exploited to obtain periodically structured materials at a nanometer scale. In the case of semiconductors, ordered arrays of crystalline dots and wires (QDs and QWRs) can be obtained during the first steps of epitaxial growth. These self-assembled nanostructures show novel and attractive physical properties related to quantum size effects improving the performances of the new design electronic and optoelectronic devices.
The QDs auto-organization is driven by the strain at the interface due to the lattice mismatch between substrate and epilayer. Above a certain thickness, that is in general of the order of a few monolayers (ML), the 2D growth is no longer stable and the excess of strain is released through the transition to a 3D morphology, i.e. the formation of islands. The process is known as the Stranski-Krastanov mode. To be suitable to fabricate devices, the nanostructures must be homogeneous in size, shape and spatial distribution, to provide well defined emission wavelengths. The Q arrays are characterized mainly in terms of optical (luminescence, photoreflectance) and vibrational properties (Raman) while AFM and TEM give an image of the shape and an idea of the homogeneity of the islands. The strain content of the Quantum structures depends on the islands dimension and it looks often to be quite inhomogeneous inside the island. The nanostructures composition is often not well known, since reactions with the substrate atoms or segregation mechanisms of the impinging species can occur[1,2]. In the present paper we report the study of InAs QWrs formed on InP(001) substrate by means of Grazing Incidence Diffraction Anomalous Fine Structure. The DAFS measurements were carried out at grazing incidence and outgoing angles close to the critical angle of InP, to enhance the contribution of the very thin epilayer with respect to the substrate. The method offers the unique advantage of combining the chemical selectivity of Extended X-Ray Absorption Fine Structure (EXAFS) with the spatial and site selectivity of X-Ray Diffraction (XRD)[2]. Thanks to the QWrs short range periodicity that gives rise to broad satellites in the reciprocal space, the spatial selectivity was achieved by choosing a momentum transfer vector, $Q$, at the maximum intensity of a satellite peak. The As local environment was probed by tuning the incident beam at the As K-edge and by measuring the diffraction fine structure as a function of the energy at constant $Q$ vector. It should be noted that P substitute for As, therefore the data analysis would have been easier at the In K-edge, however we chose not to work at the In K-edge to avoid the substrate contribution through the transmission functions. It is shown, hereafter, that GIDAFS and EXAFS data at the As K-edge are quite different, emphasizing the interest of DAFS for studying these materials. We also show preliminary results on QWrs covered with a 40 Å thick InP cap layer. The structure is in this case closer to an integrated device system, where the active layer is always encapsulated in the device unity. We want to investigate how the cap layer modifies the wires.

2. Experimental

2.1 Samples

The QWrs samples have been grown by Molecular Beam Epitaxy (MBE) at the Instituto de Microelectrónica de Madrid [1], onto (001) oriented InP substrates. The equivalent thickness of the wires is 2.2 MLs (Mono Layers). We show in Fig. 1a a typical AFM image of InAs/InP wires, with a height varying from 0.6 and 2 nm and a width of about 22 nm. The wires are oriented along the [110] crystallographic direction. In the case of the capped samples, the as-grown wires have been covered by a 40 Å thick InP capping layer.

2.2 X-Ray absorption measurements

The DAFS measurements were carried out at the French Collaborative Research Group beamline BM02 at the European Synchrotron Radiation Facility. Silicon (111) single crystals were used for beam monochromatisation, giving an energy resolution of about 1eV at the As K-edge (11.867 keV). The sample was mounted with the electric polarisation vector of the incident beam perpendicular to the sample surface. We performed the GIDAFS measurements in grazing geometry, according to the scheme of figure 1, with in incidence angle close to 1.5 times the critical
angle of InP at 12 keV ($\alpha \approx 0.3^\circ$), and kept constant during the scan. The spectra were recorded by measuring, as a function of the energy, the maximum intensity of the most intense satellite on the low side of the radial scan ($Q_r$ scan) of the substrate peak (see arrow on figure 2).

3. Data analysis

The DAFS method has the unique capability of providing long range order crystallographic information together with absorption-like short range order information. These are contained in the structure factor of the measured Bragg reflection and in the anomalous complex atomic scattering factor $f$. The latter can be split, in the forward scattering limit, into a smooth and an oscillatory part [4]:

$$f_A(\mathbf{Q}, E) = f_0(\mathbf{Q}) + f'_0(E) + i f''_0(E) + \Delta f''_0(\chi'(E) + i \chi''(E))$$

where $f_0$ is the Thomson scattering term, $f'$ and $f''$ are the smooth real and imaginary terms of $f$, $\chi'$ and $\chi''$ are the oscillatory contributions to $f$, $f'$ and $f''$ respectively. The data analysis was performed in two steps. First, a crystallographic co-refinement of the GIDAFS spectra was done using the DPU code [5], details are given in our previous paper [4]. The structure factor was calculated with the crystallographic parameters of the Zinc-Blende structure, allowing P atoms substitute for As atoms. The Bragg diffracted intensity was corrected for a transmission coefficient, $I_{\text{diff}} \propto |T_E(E)|^2 |T_E(E)|^2 |F(E)|^2$ that represents the effect of refraction, at the substrate surface, of the incoming x-ray wave. We applied the Distorted Born Wave Approximation (DBWA) [6] considering that total reflection takes place essentially at the interface with the substrate, i.e. regarding the nano-objects as a small perturbation of the electric field above the substrate. The fit parameters included scale and slope factors to take into account geometrical and detection effects. Other parameters were Debye Waller factors and the P concentration, $x$, in InAs$_{1-x}$P$_x$. The crystallographic simulations, shown on figure 3 (continuous curves), have been calculated using the experimental (oscillating) $f''$ of bulk InAs, obtained from the transmission EXAFS spectrum of a powdered sample. The real part, $f'$, of the scattering factor was calculated by a Kramers-Kronig transformation of $f''$. Smooth theoretical curves from the Cromer-Libermann tables, were used for $f'$ and $f''$ of In and P atoms. Second, we extract the oscillations above the edge, or extended DAFS (EDAFS), and analyzed them according to the EXAFS data processing scheme, to obtain the local structure parameters, as interatomic distances, coordination numbers and Debye Waller factors. The EDAFS spectra have been compared with theoretical phase and amplitudes calculated by the FEFF8 [7], by means of a best-fit procedure performed by the FEFFIT program [8]. The crystallographic fit also provide the EDAFS scale and phase factors that allow to analyze EDAFS as EXAFS data. The data analysis procedure has been described extensively elsewhere [4]. In order to check the reliability of our data analysis bulk DAFS spectrum calculated starting from EXAFS. The fit results are shown in figures 4b and 4c (continuous curves) and in Table I. The bulk InAs EXAFS spectrum (fig. 4c, panel a) was fairly fitted by using the standard crystallographic structure parameters for InAs. One multiple scattering path (MS) was not negligible and was included in the fit of the EXAFS and (420) EDAFS spectrum. It corresponds to a triangular three-atom path As--In--As. The same parameters were found, within the uncertainties, for the bulk InAs EDAFS spectrum, as expected.
4. Results

4.1 Uncapped Quantum Wires

4.1.1 Crystallographic structure

The XRD radial scan spectrum of the QWrs sample, recorded at 11.8 keV, around the (440) Bragg reflection of the substrate, is shown in figure 2. The momentum transfer vector $Q$ is oriented along the [ direction, i.e. perpendicular to the wires. The sharp Bragg peak for $\overrightarrow{Q}$ at about 0.96 Å$^{-1}$ corresponds to the (440) Bragg reflection of the InP substrate. Several satellite peaks due to the wires periodicity clearly appear close to the substrate peak. The satellites' spacing gives a wire periodicity, $\lambda = \frac{1}{\Delta Q}$, about 200 Å, in fair agreement with the AFM image. A radial scan of the (420) peak was also recorded and showed a shape very similar to (440). The GIDAFS spectra of the QWrs sample for the (440) and (420) Bragg reflections, as well as the crystallographic fits are shown in figure 3. A clear result from the fit, is that to reproduce the shape of the anomaly at the edge, we do need to include the presence of P in the epilayer. As a result of the iteration we find a P concentration $x \approx 0.5 \pm 0.1$. This shows that a considerable density of P atoms, with the same periodicity as the wires, is contributing to the satellite diffraction peaks. Owing the same periodicity as the wires. At this point, diffraction can not tell if the P atoms participating to the diffraction belong to the wires or to the InP substrate. The latter could show a periodic undulation and/or periodic strained areas due to the strain at the interface with the InAs wires.

4.1.2 Local structure

Now we report on the analysis of the diffraction fine structure. The glancing-angles (420) EDAFS oscillations, after background subtraction, are shown in figure 4a, panel (a) (dotted curve). They are compared with the EDAFS oscillations of the crystallographic fit, calculated with experimental $f'_{As}$ and $f''_{As}$ of InAs bulk (figure 4b, panel(a)). The overall behavior of the two DAFS spectra are quite similar, the contribution of the In nearest neighbor (NN) of As is indeed dominant over the contribution of next NN (NNN) that are only As in bulk InAs, and As and P in the QWrs spectrum. Nevertheless, some differences can be observed, out of the noise level of the EDAFS QWrs spectrum. It is more evident in figure 4, panel (b), by comparing the Fourier Transforms (FT) of the EDAFS spectra. The NN shell contributions are quite similar to each other, whereas the NNN peaks are different, showing a change in the NNN environment. The best fit curves for the QWrs sample are shown in figures 4a (continuous curves), and compared with the experimental EDAFS and FT (dotted curves). All the FTs reported in figure 4, panel (b) were calculated in the same range 3-11.7 Å$^{-1}$. The fit was performed on the raw data, in the R-space, in the range 1.5 5.9 Å, by iterating a maximum of 11 parameters. The As-In NN and As-As NNN distances were fixed at the values foreseen by the elastic theory for a pseudomorphic epilayer of InAs grown on InP, i.e., 2.60 Å and 4.29 Å. The As-P NNN distance has been refined and found to be equal to 4.17 Å ± 0.02 Å. The P concentration, (1-x), was also refined, giving (1-x) = 0.4 ± 0.15. It is, within the errors, equal to the value found by the crystallographic fit of the anomalous diffraction line-shape at the edge. The second shell As-P distance is quite short, close to the P-P distance in bulk InP (4.15 Å). Nevertheless the shapes of the spectra, in k- and R-spaces, were reproduced only when freeing this parameter and letting it to vary independently of the As-As distance. The shapes we are referring to correspond to the low-k range oscillations of the $\chi$ spectrum and the second shell environment in the FT, just below 4 Å, corresponding to the NNN contribution. The intensity of that contribution is much lower in the case of the QWrs in comparison with bulk InAs. It can be reproduced by adding out of phase As-P and As-As contributions with an As-P distance of 4.17 Å.

We want to note that the polarization of the incoming photons was directed along the (001) direction, i.e. perpendicular to the surface, making an angle of 90° with the NNN $R_{ij}$ vector from
the As absorber to the As (P) atoms lying in the (001) plane (in-plane-NNN). Therefore the NNN contribution to EDAFS is due only to the 8 out-of-plane NNN atoms at a distance, according to elasticity, of 4.29 Å from the As absorber. The in-plane NNN As atoms should instead show a distance, in the case of a perfect pseudomorphic layer, equal to the P-P NNN distance of InP bulk, i.e. 4.15Å. Qualitative inspection of our XRD measurements as well as previous results [9] indicate a weak relaxation along the [110] direction. An upper limit to relaxation can be given by the XRD spectrum in figure 2, considering the most intense satellite as the maximum of the broad envelope curve supposedly due to the InAs epilayer. From its position in Q we can estimate the lattice parameter and, roughly, a strain of about 2%, instead of 3.2% for the pseudomorphic case. According to elasticity, the As-In distance would change from 2.60 Å to 2.614Å. Considering that we would see an average between the two values, since the layer shows to be pseudomorphic along the [110] direction, we should expect to observe a correction to the As-In distance lower than 0.01Å, that is within the error of our measurement. The same consideration applies to the NNN As-As distance, note that it is 4.29 Å for the strained InAs and 4.27 Å for bulk InAs[10]. We also have to point out that a feature at about 4.5 Å is observed in the QWrs FT spectrum that does not show in the bulk InAs FT. It is reproduced in the fit by the MS In-As-P contribution that is not present in the bulk InAs spectrum, and appears to be quite intense for the QWrs. Measurements with a better signal-to-noise ratio are needed to clarify this effect. In any case it does not affect the evidence of a short As-P distance. Glancing-Angle EXAFS was also measured, on the same QWrs sample, by detecting the As fluorescence yield. The As-In distance was found to be of 2.60 ± 0.03Å, i.e. equal within the error, to the value found by EDAFS. Nevertheless, the surface oxide layer strongly affects the EXAFS spectrum, causing a strong loss of information, in particular for shells beyond the first one (Fig. 5). The EDAFS oscillations instead are not affected by the oxide, thanks to the site selectivity of diffraction.

4.1.3 Results on uncapped Quantum Wires
In this work we show that DAFS, can be applied, in grazing geometry, to the study of self assembled nanostructured materials representing an extremely low equivalent coverage of about 2.5 MLs. We performed crystallographic and EDAFS analysis of the (440) and (420) GIDAFS spectra, and compared the information. In particular we obtained the composition and strain inside the wires. The quality of the spectrum may be improved using higher brilliance beamline, nevertheless the signal-to-noise ratio of our spectra allowed quantitative analysis. We have shown that, in both spectra, we detect the presence of a consistent amount of P atoms, (1-x) = 0.4±0.1. Does it means that the quantum wires are grown as InAs$_{0.5}$P$_{0.5}$/InP? We can answer by comparing the values of the interatomic distances with the values found for bulk and superlattice InAsP samples in a recent work[10]. One must note that in our case the polarization vector of the electric field of the X-ray incident beam was perpendicular to surface plane (001), whereas it was in the surface plane in the cited paper. The NNN distance, $R_2$, for As-As and As-P pairs, reported by the authors, can be approximated by the weighted average of the in-plane and out-of-plane distances, according to the expression

$$R_2 = \frac{N_\perp R_{2\perp} + N_\parallel R_{2\parallel}}{N_\perp + N_\parallel}$$

where $N_\perp$ and $N_\parallel$ are the out-of-plane and in-plane coordination numbers, corrected for polarization and finite thickness of the epilayer (for 3ML, $N_\perp/N_\parallel \approx 4/6$). The values they found at x = 0.4 for $R_2$, are about 4.19 and 4.2 Å for As-P and As-As respectively. We can estimate the out-of-plane NNN distance from the former expression assuming pseudomorphicity, i.e. taking $R_\perp$ as P-P distance in bulk InP (4.15 Å), and using the former experimental $R_2$ values. We obtain 4.25 and 4.28 Å for $R_{2\perp}$, As-P and $R_{2\perp}$ As-As respectively, i.e. a NNN distance value for the As-P pair much higher than the value of 4.17Å, our experimental value. In the case of the relaxed bulk InAsP alloy, we would see the same relaxed NNN distance for the in-plane and out-of-plane atoms. The values found in
reference [10] are 4.26 Å for the As-As pair and 4.22 Å for the As-P pair. The As-P distance is again appreciably longer than the value we have found. This result suggests therefore that, due to the low epilayer thickness and to the X-ray beam polarization, the interface effects on the EDAFS spectrum are remarkable, i.e., the P atoms contributing to EDAFS have to belong to the interface region between InAs and InP, therefore the core of QWrs is essentially InAs. We cannot have an abrupt, atomically flat InAs/InP interface since in that case, the P concentration, obtained by EDAFS, measured with [001] polarization, should be (1-x) ≅ 0.3, due to the fact that the As atoms belonging to the first InAs ML, have P atoms of the InP substrate as NN neighbors, at distance of about 4.20 Å. The value that we find experimentally for P concentration is higher and the As-P distance is shorter. Moreover, no P contribution to the DAFS line-shape at the edge should be found according to this model, whereas the crystallographic fit shows a P concentration close to that found by EDAFS. The high P content seen by diffraction can be explained by an abrupt InAs/InP interface with periodic InP strained regions generated in the InP buffer layer, beneath the wires, or a corrugated InAs/InP interface with the same wires periodicity. The interface formation mechanisms are known to be quite complex. The As atoms can be incorporated indeed, at the InP surface, between 0.5 and 1.5 MLs, during P/As switch prior to In deposition for InAs growth[9]. A sort of corrugation of the InP substrate could be produced by As incorporation on the P-rich buffer layer surface, forming elongated islands along the [1 1 0] direction. This has been observed in AFM studies of the first growth steps of InAs/InP[2]. On the other hand, the short As-P distance is in agreement with a small contraction of the InP lattice parameter in proximity to the interface, due to the tensile strain on InP. Therefore our results suggest that we are observing a corrugated interface and buffer layer deformation at the same time.

4.2 Capped Quantum Wires

4.2.1 Simulation of elastic relaxation

We carried out a simulation of elastic relaxation in an array of InAs wires embedded in InP by the Finite Element Method [11]. Since the wires are fully strained along the [1-10] direction, the relaxation is simulated using rectangular cells of initials width √2aInP (along [110] also called x) and aInP height ([001] or z). We assumed a perfectly periodic structure (200Å wire to wire distance), with no dislocations and sharp InP/InAs interfaces. The shape of the wires is a first guess. Atoms are placed in the relaxed building units : In atoms are located at the cell nodes (000) whereas As an P atoms are placed taking according to the cell deformation. The diffraction intensity is then calculated in the grazing geometry using the DWBA approximation, taking also into account the finite scattering length in the z direction :

\[ I_{\text{diff}} \propto |T_{\epsilon,E}(E,\alpha_i)|^2 |F(E,\Omega)|^2 |T_{\epsilon,E}(E,\alpha_j)|^2 \]

where \( T_{\epsilon,\Omega} \) and \( F \), are the transmission and structure factor respectively. The diffraction intensity was calculated with experimental \( f''_{\text{As}} \) and \( f''_{\text{As}} \) of InAs bulk, all other anomalous scattering factors were taken from theoretical calculations. The results are shown in figures. 6a and 6b where the different colours of the painting put in evidence the different regions of dilatation and compression with respect to the InP lattice parameter. In figure 6a, the relative strain \( \epsilon_{\text{xx}} = (a_{\text{InP}} - a_{\text{InAs}})/a_{\text{InP}} \) is given along the x direction ([110]), whereas in figure 6b, \( \epsilon_{\text{zz}} \) is given along the z direction ([001]), i and j represent the cell coordinates. The iso-strain maps show that InAs is strongly strained by to the substrate in the x direction, the maximum relaxation in InAs regions is about 1%, this must be compared to the maximum of relaxation of 3.2%. One can also notice that the +0.5% iso-strain region contains about 50% of InP cells. In the [001] direction instead, the strain in the wire is almost uniform and quite large ( ). The
displacement field gives rise to a spreading of the diffuse scattering in the reciprocal space according to the d-spacing. Therefore, roughly speaking, choosing a $\mathbf{Q}$ vector means selecting an iso-strain region. Anomalous diffraction and DAFS will then help to recover the average atomic composition as well as the local structure [12]. The reciprocal space scheme of Fig. 7, shows the (420) Bragg peak together with the satellite peaks due to the QWRs periodicity. The $\mathbf{Q}$ scan line schematically shown in figure 6c) was performed to minimize the substrate contribution. However, for completeness a detailed mapping of the reciprocal space is needed.

4.2.2 DAFS measurements on encapsulated Quantum wires

We performed preliminary DAFS measurements at the D2AM french ESRF beamline at the As K-edge in the grazing geometry, as for the uncapped wires. The experiment is challenging, since the wires, due to the presence of the cap layer, almost match InP in the [110] direction, so the InAs cell parameters are very close to that of InP. As for the uncapped wires, we chose to measure the diffuse scattering close to the weak Bragg reflection (240), in order to obtain a strong anomalous contrast. Fig. 7 shows the $\mathbf{Q}$ scans at two different energies, one below the As K-edge (11.857 keV) and the other at the edge (11.867 keV). The scans were performed as shown in the scheme of Fig. 7, in order to avoid the InP substrate peak and to enhance the diffraction structures (labelled S1, S2 and S3), that are wider than the average and substrate peaks along the [110]* direction. We can see that the anomalous effect does depend on $\mathbf{Q}$. It is negligible for peak S1 whereas it is stronger for peak S3 than for S2. The satellites S1 and S2, appear as correlation peaks of the main reflection (substrate peak position), since they correspond to about 200Å. The FEM and the diffraction simulations (figure 7b) show that S2 correspond to a compressed InP region, explaining why no anomalous effect is detected at the As K-edge, whereas S1 corresponds a region under a tensile strain of 0.5% comprising InAs as well as InP. On the other hand, S3 is not a correlation peak and corresponds to a relaxation rate of (2 %), the strong anomalous effect means that there exist uncorrelated regions of composition close to InAs. We demonstrate here the ability to probe different regions of different strain and composition.

We show the DAFS spectrum taken at the S1 ($\varepsilon_{xx}=0.5\%$) peak in Fig.8, together with the correspondent crystallographic fit. The jump at the edge and the shape of the anomaly give us information on the As content of the selected region. We found an average P concentration, $x\approx0.5$, similar to the case of uncapped QWRs. The signal to-noise-ratio is not yet good enough to allow a quantitative EDAFS analysis, to extract composition and distances, and the spectrum quality should be improved. It would be very interesting to measure DAFS on the top of the S3 peak. The anomalous effect is stronger but will be the fine structure different?

5. Conclusions

As a general conclusion, we performed a GIDAFS study to investigate the structural properties of self-assembled QWRs. We have shown that this techniques can elucidate the displacement fields and the chemical composition. The local order can be spatially resolved, and we can get information on the interface nature. All this information is of great importance in the design of this atomic-scale device unities, which depends on the growth technique and determines their performance properties. Precise anomalous diffraction mapping is now needed, to get a complete crystallographic picture of the system together with theoretical simulation of the displacement field and interdiffusion as well as rigorous calculation of the X-ray scattering of embedded nanostructure in the grazing geometry in order to interpret the reciprocal space maps and recover the crystallographic structure.

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References
Table captions:

Table 1: Best fit results for the bulk powder InAs EXAFS and the corresponding simulated EDAFS (italic).

Figure captions:

Figure 1: AFM tridimensional view of InAs QWrs on InP buffer from[2] with a scheme of the glancing angle diffraction measurement.

Figure 2: (440) XRD intensity of QWrs sample, as a function of the momentum transfer, recorded in glancing-angle geometry at 11.8 KeV.

Figure 3: (440) and (420) Grazing Incidence DAFS spectra of the QWrs sample, at the As K-edge (dotted curves) and crystallographic fits (continuous curves).

Figure 4: Panel (a): Grazing incidence (420) EDAFS of InAs QWrs at the As K-edge (a) compared with the (420) EDAFS of the crystallographic fit (b) and EXAFS of bulk InAs (c).
Panel (b): Fourier transforms of the panel (a) spectra. The best fits for each spectra are also shown as continuous curves.

Figure 5: Panel (a): Grazing incidence EXAFS of InAs QWrs. Panel(b): the Fourier transform, with the best fit as continuous curves, including As-O and As-In single scattering paths.

Figure 6: Iso-strain maps. Finite Difference calculations of a) $\varepsilon_{xx} = (a_{ij} - a_{inP})/a_{inP}$ ([110] direction) and b) $\varepsilon_{zz} = (a_{ij} - a_{inP})/a_{inP}$ ([001] direction) maps (i and j represent the cell coordinates). The base and height of the wire are about 180Å and 40 Å, respectively. The cap layer is about 50 Å thick.

Figure 7a : Schematic representation of the hk0 reciprocal plane, emphasizing the Qr scan around the (240) performed in grazing incidence geometry.

Figure 7b : Experimental diffraction data corresponding to the Qr scan around the (240) schematically represented in figure 7a, together with the diffraction intensity calculated with the crystallographic structure of figure 6.

Figure 8 : DAFS spectrum at the As K-edge measured at the S1 peak position with $\alpha = 1.5 \cdot \alpha_0$ ($\approx 0.3^\circ$).