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Sohail, H. M., Uhrberg, R. I. G., (2016), Experimental studies of an In/Pb binary surface alloy on Ge(111), *Surface Science*, 649, 146-151. <https://doi.org/10.1016/j.susc.2016.02.016>

Original publication available at:

<https://doi.org/10.1016/j.susc.2016.02.016>

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Experimental studies of an In/Pb binary surface alloy on Ge(111)

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Abstract

In this study, we present a binary In/Pb surface alloy on Ge(111) formed by evaporating In on the Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ β phase. A well-defined 3×3 periodicity is formed after annealing, as verified by both low energy electron diffraction (LEED) and scanning tunneling microscopy (STM). Overview STM images show a clear 3×3 periodicity. Detailed STM images reveal protrusions corresponding to atomic sized features with a local hexagonal arrangement. Each 3×3 unit cell contains nine such features indicating a structure with 9 atoms per 3×3 cell in the topmost layer. Based on angle resolved photoelectron spectroscopy (ARPES) data, we have identified five surface bands within the bulk band gap. Four of them cross the Fermi level leading to a metallic character of the surface. The dispersions of these bands have been mapped in detail along two high symmetry directions of the surface Brillouin zone. Constant energy contours, mapped in two dimensional k-space, show interesting features. In particular, the occurrence of two differently rotated hexagon like contours is presented.

Keywords: Ge(111), Lead (Pb), Indium (In), monolayer, LEED, STM and ARPES.

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1. Introduction

Metals adsorbed on semiconductor surfaces are important since they provide well-ordered one or two dimensional structures useful for the study of various physical phenomena [1]. Most of such studies have been restricted to a single metallic species, while the combination of two metals has not been given similar attention. In a few studies, a tiny amount (0.1 - 0.2 monolayers (ML)) of a second metal has been added to a well-defined monolayer formed by the initial metal. In some cases, this results in new reconstructions due to periodic positions of the added metal atoms [2-5]. This kind of surface is, however, not considered to be a binary surface alloy. In an effort to form binary surface alloys, we have investigated several combinations of metals on elemental semiconductor surfaces, of which the combination of Ag and Sn has been reported which forms well-ordered binary surface alloys [6-8]. In those studies, we utilized the well-defined and well-ordered Ag/Ge(111) $\sqrt{3}\times\sqrt{3}$ and Ag/Si(111) $\sqrt{3}\times\sqrt{3}$ surfaces as substrates which have been very well studied [9-16]. Other well studied surfaces that could act as suitable substrates are formed by Pb on Si(111) or Ge(111) [17-24]. In this study we used the Pb/Ge(111) $\sqrt{3}\times\sqrt{3}$ surface formed by 1.33 ML of Pb [22-24] as a substrate. The addition of In resulted in an ordered In/Pb/Ge(111) surface alloy having a 3×3 periodicity.

We present a detailed investigation of the atomic and electronic structures of the In/Pb/Ge(111) 3×3 surface alloy. Scanning tunneling microscopy (STM) images obtained at 50 K reveal atomic sized features with a local hexagonal arrangement. Each 3×3 unit cell contains nine such features indicating a structure with 9 outermost atoms per 3×3 cell. Angle resolved photoelectron spectroscopy (ARPES) was used to obtain band dispersions along two symmetry lines of the surface Brillouin zone (SBZ). We have identified five surface bands within the projected bulk band gap. Four of them cross the Fermi level leading to a metallic character of the surface. Constant energy contours of the metallic bands, mapped in two dimensional (2D) k-space, show interesting features. In particular, two differently rotated hexagon like contours show that the two metallic bands forming these contours are degenerate along $\bar{\Gamma}-\bar{M}_{1\times 1}$ and $\bar{\Gamma}-\bar{K}_{1\times 1}$. Similar rotated constant energy contours provided key information on the atomic structure of the Sn/Ag/Si(111) 2×2 surface alloy [7]. Photoemission spectra obtained from the Pb 5*d* and In 4*d* core levels show narrow line shapes with no obvious shifted components. This indicates a well-

defined environment for the In and Pb atoms and that the binary surface alloy has a high degree of structural order.

2. Experimental details

A Ge(111) sample doped with Sb was cut from a single crystal wafer with a resistivity of 7-10 Ω cm at room temperature. Initially, the substrate was cleaned *ex-situ* by acetone and isopropanol and *in-situ* by multiple Ar⁺ ion (1 keV) sputtering and annealing cycles which resulted in an atomically clean Ge(111) surface with a c(2×8) periodicity, as verified by low energy electron diffraction (LEED). Pb was evaporated from a filament source at a rate established by a quartz crystal thickness monitor. An amount of 1.33 ML was deposited at a rate of 0.5 ML/min, where one ML is defined by the number of atoms per unit area on the unreconstructed Ge(111)1×1 surface (i.e., 7.2×10^{14} atoms/cm²). Subsequent post annealing of the sample at 200 °C for a few minutes resulted in a well ordered Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surface. The addition of In in the range of 0.6 to 1.0 ML resulted in well-defined 3×3 LEED patterns after annealing at ≈ 200 °C for 1 minute. The sample studied here was prepared by adding 0.85 ML of In which is close to the middle of this range. All surfaces were prepared in a UHV chamber equipped with In and Pb evaporators, a sputter gun, a mass spectrometer and a LEED optics. The base pressure of the UHV system was $< 1 \times 10^{-10}$ Torr, while it stayed below 4×10^{-10} Torr during surface preparations. The electronic structure was investigated by ARPES in a separate UHV chamber equipped with a SPECS Phoibos 100 electron analyzer and a LEED optics for azimuthal alignment. Beamline I4 at the MAX-III storage ring of the MAX-lab synchrotron radiation facility in Lund, Sweden, was used for the ARPES study. This beamline provides linearly polarized UV and soft x-ray light in the energy range of 13 to 160 eV. The ARPES data presented in the paper were obtained at photon energies of 30 and 52 eV, with a total energy resolution of 50 meV and an angular resolution of $\pm 0.3^\circ$.

The atomic structure was investigated by STM at Linköping University. All surface preparations for the STM studies were similar to what is defined above for the ARPES study. The STM has a W-tip which was electrochemically etched *ex-situ* and cleaned *in-situ* by electron beam heating. All STM experiments were performed at ≈ 50 K in the constant current mode (200 pA).

3. Results and discussion

3.1 Atomic structure

Figures 1(a) and 1(b) show LEED results obtained at RT of the clean Ge(111)c(2×8) and Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surfaces, respectively. Figures 1(c) and 1(d) show LEED results of the In/Pb/Ge(111)3×3 surface obtained at RT using two different electron energies.. The sharp diffraction spots (some spots in Fig. 1(c) are labeled for guidance) in each LEED pattern indicate that all surfaces are well-ordered.

Fig. 1 (a) and (b) LEED patterns of the Ge(111)c(2×8) and Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surfaces, respectively. (c) and (d) LEED patterns of the In/Pb/Ge(111)3×3 surface obtained at two different electron energies.

The atomic structure was investigated by STM at ≈ 50 K and the results are presented in Fig. 2. Figures 2(a) and 2(b), show large (212×212 nm²) and small (20×20 nm²) scale empty state STM images of a clean Ge(111)c(2×8) surface, respectively, verifying that the starting surface was very well-ordered and atomically clean. Figure 2(c) shows an overview image (145×145 nm²) of a Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surface prepared by adding 1.33 ML of Pb to the surface shown in Figs. 2(a) and 2(b). The surface exhibits steps and islands on the terraces. The $\sqrt{3} \times \sqrt{3}$ periodicity is clearly visible in the small scale ($\approx 9 \times 9$ nm²) empty state image in Fig. 2(d), obtained at a sample bias of +1.5 V, showing a hexagonal arrangement of blobs. Figures 2(e)–2(h), show STM images

of the In/Pb/Ge(111) surface exhibiting a 3×3 periodicity, which is formed by adding In to the surface shown in Figs. 2(c)–2(d).

Fig. 2 (a) and (b) Large scale ($212\times 212\text{ nm}^2$) and small scale ($20\times 20\text{ nm}^2$) empty state STM images of the Ge(111)c(2×8) surface, respectively, obtained at RT. (c) and (d) Large scale ($145\times 145\text{ nm}^2$) and small scale ($\approx 9\times 9\text{ nm}^2$) empty state images of the Pb/Ge(111) $\sqrt{3}\times\sqrt{3}$ surface, respectively, obtained at RT. (e) and (f) Large scale ($342\times 342\text{ nm}^2$) and zoomed in ($46\times 46\text{ nm}^2$) empty state STM images of the In/Pb/Ge(111) 3×3 surface, respectively, obtained at $\approx 50\text{ K}$. (g) and (h) Atomically resolved empty and filled state images ($\approx 5\times 5\text{ nm}^2$), respectively, of the same surface as in (e) and (f). Unit cells of the 3×3 structure are included in (g) and (h). Nine well-resolved blobs can be identified per unit cell.

In Fig. 2(e), a large scale ($342 \times 342 \text{ nm}^2$) empty state image shows islands on wide terraces. Figure 2(f) shows a zoomed in image ($46 \times 46 \text{ nm}^2$) of Fig. 2(e), revealing details of the flat terraces which exhibit a 3×3 periodicity as clearly seen. Figures 2(g) and 2(h) are small scale empty and filled state images ($5 \times 5 \text{ nm}^2$) presenting the atomically resolved structure of the surface, obtained at $\pm 0.3 \text{ V}$, respectively. Unit cells, representing the 3×3 periodicity, are included in 2(g) and 2(h). Nine small blobs are visible in each cell in Fig. 2(g), suggesting a structure with 9 characteristic atoms per 3×3 cell. All STM images were obtained in the constant current mode (200 pA). Figures 2(a)–2(d) and 2(e)–2(h) were obtained at RT and at 50 K, respectively.

3.2 Electronic structure

Figure 3 presents the detailed electronic structure of the initial Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surface and the In/Pb/Ge(111) 3×3 surface alloy obtained by ARPES at 100 K. The ARPES data are presented in the form of emission intensity plots and as plots of the second derivative of emission intensity performed along the energy axis. Generating the second derivative is a common procedure to make also weak but well-defined structures visible. However, since the derivation is made along the energy axis, the visibility of dispersions that are very steep will not benefit from this treatment of the original data. The most complete picture of the electronic structure is obtained by extracting information from both the intensity plots and the enhanced presentation of the data in the second derivative plots. The $k_{\parallel}$ values of the symmetry points in Fig. 3 correspond to those of a $\sqrt{3} \times \sqrt{3}$ SBZ. Figures 3(a)–3(d) show the electronic structure of the Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surface. In Figs. 3(a) and 3(c) dispersions along the $\bar{\Gamma} - \bar{M} - \bar{\Gamma}$ direction of the $\sqrt{3} \times \sqrt{3}$ SBZ are presented. There are four surface bands along this symmetry line within the gap region labeled S_1 – S_4 . The S_1 band is centered at the $\bar{\Gamma}$ -points with an energy of -0.8 eV. The band disperses upward toward $\bar{M}$ -points and crosses the Fermi level. The S_1 band was reported to show a Rashba split [23] that is not resolved in our data. There is a second band, S_2 with an energy minimum at the $\bar{\Gamma}$ -points. A third band, S_3 , exists below S_2 with an energy minimum of -2.35 eV at the $\bar{\Gamma}_1$ -points. The band clearly disperses upward away from $\bar{\Gamma}_1$ with an energy maximum of -0.8 eV at $\bar{M}_2$ -points. At the $\bar{M}_2$ -point, a band S_4 shows a maximum energy of -1.3 eV and it disperses downward toward $\bar{\Gamma}$ -points. Figures 3(b) and 3(d) show band dispersions

along the $\bar{\Gamma}-\bar{K}-\bar{M}$ direction of the $\sqrt{3}\times\sqrt{3}$ SBZ. There are three bands along this direction labeled S_5 – S_7 . The S_5 band which is found within 0.2–0.6 below E_F , is most evident in the $\bar{K}_1-\bar{M}_1-\bar{K}_2$ region of the SBZ. This band shows an energy minimum of -0.6 eV at the $\bar{M}_1$ -point. In the negative $k_{\parallel}$ direction at -1.35 Å⁻¹, there is a band, S_6 , at an energy of $\approx$ -0.4 eV. This band is also observed in the positive $k_{\parallel}$ direction but it is very weak. In the energy range between 0.8 and 1.0 eV below E_F there is a band, S_7 , which shows a local energy maximum of -0.8 eV at the $\bar{M}_1$ -point. Our data on the surface band structure of Pb/Ge(111) $\sqrt{3}\times\sqrt{3}$ are in good agreement with the results presented in Ref. [24] except that the S_4 band was not mentioned in that study. However, a band similar to S_4 is also present in the data of Ref. [24].

Centered at the $\bar{\Gamma}$ -point, there are four bands, labeled S_{R1} – S_{R4} , dispersing downward. Similar bands have been reported earlier for Pb/Ge(111) $\sqrt{3}\times\sqrt{3}$ and other related systems [22, 25, 26]. The bands were reported to have a two-dimensional character since their dispersions did not change with photon energy. These bands overlap the projected bulk band structure and have therefore the character of surface resonances. More specifically, the bands were identified as two-dimensional subsurface bands closely related to the heavy hole, light hole and spin-orbit split bands of bulk germanium. Based on the results in Refs. [22, 25, 26] we attribute S_{R1} – S_{R4} to subsurface resonance bands. Further details of these bands can be found in Refs. 22, 25 and 26. In this paper we concentrate on the bands in the gap region.

ARPES data from the In/Pb/Ge(111) 3×3 surface are presented in Figs. 3(e)–3(h). Lines indicating the symmetry points of the $\sqrt{3}\times\sqrt{3}$ SBZ are also included in the panels. This simplifies the comparison between the data from the two surfaces. Some of the dispersive features correspond to surface bands in the gap region (A_1 – A_5), while other bands centered at the $\bar{\Gamma}$ -point are surface resonances (S_{R1} – S_{R4}) similar to the Pb/Ge(111) $\sqrt{3}\times\sqrt{3}$ case shown above. Figures 3(g) and 3(h) show the second derivative along the energy axis of the data in the gray scale images.

Fig. 3 (a), (b) and (e), (f) Gray scale images of the ARPES data of the Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ and the In/Pb/Ge(111) 3×3 surfaces along the $\bar{\Gamma}-\bar{M}-\bar{\Gamma}$ and $\bar{\Gamma}-\bar{K}-\bar{M}$ high symmetry lines of the $\sqrt{3} \times \sqrt{3}$ SBZ. The symmetry points included in (a) – (h) correspond to the $\sqrt{3} \times \sqrt{3}$ SBZ. A photon energy of 30 eV was used and the sample temperature was ≈ 100 K. (c), (d) and (g), (h) Figures showing the second derivative along the energy axis of the photoemission intensity data in (a), (b) and (e), (f), respectively. Surface bands are labelled as S_1-S_7 and A_1-A_5 for $\sqrt{3} \times \sqrt{3}$ and 3×3 surfaces, respectively. $S_{R1}-S_{R4}$ centered at the $\bar{\Gamma}$ -point are surface resonance bands. In the second derivative panels, solid curves are included to show the upper edge of the bulk bands projected on the 1×1 SBZ. The bulk valence band maximum has been placed at the top of S_{R3} . The corresponding position in Ref. [26] was identified as the valence band maximum.

The surface resonance bands of In/Pb/Ge(111) 3×3 are quite similar to those of Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$, while the surface band structure shows some significant changes. First we describe the In/Pb/Ge(111) 3×3 surface bands in the gap region in order to compare their dispersions with some of the $\sqrt{3} \times \sqrt{3}$ bands. There are five surface bands (A_1-A_5) within the projected bulk band

gap. Figures 3(e) and 3(g) show band dispersions along $\bar{\Gamma}-\bar{M}-\bar{\Gamma}$. A surface band, $A_{1,2}$, that crosses the Fermi level at $k_{\parallel} \approx \pm 0.45 \text{ \AA}^{-1}$ disperses down to $\approx -0.65 \text{ eV}$ at $k_{\parallel} \approx \pm 0.65 \text{ \AA}^{-1}$. Further out in the SBZ it cannot be followed clearly. Along $\bar{\Gamma}-\bar{K}-\bar{M}$, a band, A_2 , crosses the Fermi level at $k_{\parallel} \approx \pm 0.35 \text{ \AA}^{-1}$ and disperses downward to $\approx -0.85 \text{ eV}$ at $\bar{K}_1$ -points. For negative $k_{\parallel}$ values the dispersion can be followed down to $\approx -1.0 \text{ eV}$ at the $\bar{M}_1$ -point, see Figs. 3(f) and 3(h). Below, it is shown from constant energy contour data that there is a crossing between two bands along the $\bar{\Gamma}-\bar{M}-\bar{\Gamma}$ (see Fig. 5 along $\bar{\Gamma}-\bar{K}_{1\times 1}$) direction resulting a doubly degenerate band. Thus, we have labeled the band as $A_{1,2}$. There are two more bands, A_3 and A_4 , which are degenerate along both $\bar{\Gamma}-\bar{M}$ and $\bar{M}-\bar{K}$ lines, labeled $A_{3,4}$. These degenerate bands have energy minima at -0.8 eV and -0.6 eV at the $\bar{\Gamma}_1$ and $\bar{M}_1$ -points, see Figs. 3(g) and 3(h), respectively. The degenerate A_3 and A_4 bands form two rotated distorted hexagons when mapped in 2D k-space, see the next section. The surface bands, A_1-A_4 , all disperse across the Fermi level resulting in a metallic character of the surface alloy.

3.3 Constant energy contours

In Fig. 4, we present constant energy contours obtained by ARPES for the Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ and the In/Pb/Ge(111) 3×3 surfaces using a photon energy of 30 eV at RT. The figures show the same region of the $\sqrt{3} \times \sqrt{3}$ SBZ in order to compare the contours of the two different surfaces. Both contour plots in Fig. 4 correspond to an energy of 0.1 eV below E_F . Fermi contours are less clear because of lower intensity and are not shown here. Figure 4(a) shows parts of hexagonal contours due to the S_1 band. Along the $\bar{K}_1-\bar{M}_1$ line the brightness is due to some vertical intensity between the S_5 band and the Fermi level, which was also present in the data of Ref. [22], see also Fig. 3(d). In Fig. 4(b), the contour map of In/Pb/Ge(111) 3×3 in the same region shows two very distinct intersecting contours from the A_3 and A_4 surface bands. These bands are degenerate along $\bar{M}_1-\bar{\Gamma}_1$ and $\bar{K}_1-\bar{M}_1$, see Fig. 4(b). A detailed constant energy contour map of the In/Pb/Ge(111) 3×3 surface is given in Fig. 5 below.

Fig. 4 (a) and (b) Two dimensional constant energy contours generated from the ARPES data obtained from the Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ and In/Pb/Ge(111) 3×3 surfaces, respectively. The bright features represent high photoemission intensity. The hexagonal shaped S_1 contour of the Pb/Ge(111) $\sqrt{3} \times \sqrt{3}$ surface is replaced by two rotated distorted hexagons on In/Pb/Ge(111) 3×3 surface. The contours of A_3 and A_4 in (b) intersect each other along both the $\bar{\Gamma}-\bar{M}_1-\bar{\Gamma}_1$ and $\bar{\Gamma}-\bar{K}_1-\bar{M}_1$ lines. The black hexagons in (a) and (b) represent the $\sqrt{3} \times \sqrt{3}$ SBZ.

Figure 5 shows detailed constant energy contours of the In/Pb/Ge(111) 3×3 surface obtained for the surface bands (A_1-A_4) and the surface resonance bands $S_{R1}-S_{R4}$ that are indicated by the corresponding labels. We have chosen an energy of 0.4 eV below E_F , so that both surface and surface resonance band contributions to the contour map are included. Contours obtained at the Fermi level, do not show the contours of all the $S_{R1}-S_{R4}$ bands clearly and are therefore not included here. The right half of Fig. 5, (i.e. positive k_x) shows the original photoemission data while the left half shows the same data but rotated 180° around $\bar{\Gamma}$. This is done just for an easier visualization of the symmetry of the contour map. The S_{R1} band exhibits a flower like contour which reaches furthest away from the $\bar{\Gamma}$ -point in the $\bar{\Gamma}-\bar{K}_{1 \times 1}$ direction. The band, S_{R2} , represents a distorted hexagonal contour next to the outermost one. The innermost bands, S_{R3} and S_{R4} , at -0.4 eV, cannot be resolved and these two bands give rise to a circular constant energy contour close to the $\bar{\Gamma}$ -point. In addition, the surface bands A_1 and A_2 exhibit a crossing along $\bar{\Gamma}-\bar{K}_{1 \times 1}$. The contours of these two bands look like part of a circle that is not centered at the $\bar{\Gamma}$ -point. The curvature of the A_1 and A_2 circular contours point to the $\bar{\Gamma}$ -points of neighboring 1×1 SBZs as the centers. It is interesting to note that the contours of the A_3 and A_4 bands give rise to two rotated hexagon-like contours that intersect each other along the two symmetry lines, see Fig. 5. Thus, these two bands are degenerate along $\bar{\Gamma}-\bar{M}_{1 \times 1}$ and $\bar{\Gamma}-\bar{K}_{1 \times 1}$.

Fig. 5 Detailed two dimensional constant energy contour map of the In/Pb/Ge(111)3×3 surface obtained from ARPES data at RT using a photon energy of 30 eV. The bright features represent high photoemission intensity. The bands closest to the $\bar{\Gamma}$ point are due to the surface resonances S_{R1} – S_{R4} and A_1 – A_4 show surface band contours. The contours of A_1 and A_2 intersect each other along $\bar{\Gamma}$ – $\bar{K}_{1\times1}$ which shows that these two bands are degenerate in this direction. Similar crossings are observed for the A_3 and A_4 contours along both $\bar{\Gamma}$ – $\bar{M}_{1\times1}$ and $\bar{\Gamma}$ – $\bar{K}_{1\times1}$, which verifies that A_3 and A_4 are degenerate in both of these directions. Note that the white arrows point towards $\bar{M}$ and $\bar{K}$ points of a 1×1 SBZ.

In Fig. 6, we have plotted constant energy contours obtained at a photon energy of 52 eV. An energy of 0.4 eV below E_F was chosen in order to include contributions from both surface states and surface resonances to the contour map, and to facilitate a comparison with the contour map in Fig. 5. The features due to the S_{R1} – S_{R4} bands and A_1 – A_2 are clearly observed, which verifies the somewhat fuzzy contours near the $\bar{\Gamma}$ -point in Fig. 5. More importantly, the contributions from the S_{R1} – S_{R4} bands in the contour map of Fig. 6, confirm the shapes of the less clear contours around $\bar{\Gamma}$, in Fig. 5.

Fig. 6 Two dimensional constant energy contours generated from the ARPES data obtained from the In/Pb/Ge(111)3×3 surface at RT with a photon energy of 52 eV. The origins of the contours in terms of surface bands (A_1 and A_2) and the surface resonance (S_{R1} – S_{R4}) are indicated by the corresponding labels. The center of the contour plot corresponds to the $\bar{\Gamma}$ -point of the SBZ.

3.4 Core level spectra

A spectrum showing the In 4*d* and Pb 5*d* core levels are shown in Fig. 7(a), while the Ge 3*d* spectrum is shown in Fig. 7(b). The Pb 5*d* spectrum was fitted by two spin-orbit split components (the larger component being totally dominating), while the In 4*d* spectrum was fitted by just one spin-orbit split component. Both the Pb 5*d* and the In 4*d* core levels were fitted using a Doniach-Šunjić line profile [27]. The absence of shifted components indicates that both the In and Pb atoms have a well-defined environments, which is also supported by the high degree of structural order observed by STM for this surface alloy. The Ge 3*d* spectrum has a quite broad and featureless shape which could be fitted by three spin-orbit split components, but it is difficult to extract any structural information from such a broad spectrum.

Fig. 7 (a) Spectrum including the In 4d and Pb 5d core levels obtained at a photon energy of 60 eV. (b) Ge 3d spectrum obtained at 80 eV. The narrow line shapes of the In 4d and Pb 5d spectra indicate a well-ordered structure of the In/Pb surface alloy. The Ge 3d spectrum is quite broad and has featureless characteristics.

4. Conclusions

A well-ordered In/Pb binary surface alloy has been prepared on the Ge(111) surface. As revealed by ARPES, the surface shows an interesting electronic band structure from which we have clearly identified five surface bands within the projected bulk band gap. Constant energy data revealed the existence of two rotated hexagon-like contours formed by two bands which are degenerate along the $\bar{\Gamma}-\bar{M}_{1\times 1}$ and $\bar{\Gamma}-\bar{K}_{1\times 1}$ directions. Detailed STM images show that there are nine blobs per 3×3 unit cell indicating the presence of 9 atoms in the outermost atomic layer. The In/Pb/Ge(111) 3×3 surface is an exceptionally well-ordered binary surface alloy having metallic character. The two rotated hexagon-like constant energy contours, formed by the A₃ and A₄

bands, provide crucial information related to the detailed atomic structure of the surface alloy. Among the large number of possible binary combinations of atomic species, it is likely that several well-ordered surface alloys will be discovered. Of these, some may exhibit exotic properties, which acts as an inspiration for this kind of studies.

Acknowledgements

Technical support from Dr. Johan Adell and Dr. T. Balasubramanian at MAX-lab is gratefully acknowledged. Financial support of the research work was provided by the Swedish Research Council (VR) and the Knut and Alice Wallenberg Foundation (KAW).

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