Atomic Structures of Au and Ag Films Epitaxially Grown on the InP(001)-p(2×4) Surface

K. Morita, K. Soda, T. Katoh and M. Hanebuchi

Department of Crystalline Materials Science,
School of Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-01, JAPAN

Introduction

The metal-InP system is of special interest, because of its potential use in high-speed logic, integrated optics and micro wave applications. Nevertheless, there have been a few epitaxial metallization systems of metal and metal compound reported on InP.[1-3] Metal/InP systems are believed to be chemically reactive and the metal reacts with In and/or P to form a mixture of metal-indium and metal-phosphorous compound by high temperature anneals[4,5]. However, we have shown, for the first time, the epitaxial growth of a mono-crystalline AuIn compound on InP(001) by annealing a Au/In(001)-p(2×4) system at temperatures of 250~300°C which has been prepared under an ultra high vacuum condition, [6]. Very recently, we have observed by means of LEED, AES and RBS-channeling techniques that Au films grow epitaxially in the layer-by layer mode along the [001] direction on the InP(001)-p(2×4) surface by room temperature deposition under a UHV condition[7]. The low temperature epitaxy has been explained in terms of self-annealing due to heat of mixing released in the exothermic interface reaction of Au and In.

Such a low temperature epitaxy is useful for development of the InP devices. Moreover, it has been observed that Ag films grown in the [011] direction in the Stranski-Krastanov (S-K) mode and the islands of Ag(110) crystallites preper to orient their (001) side surface along the direction of 4 times supper lattice, which has been obtained by means of the additional RHEED technique.[8]

In this paper, we compare the atomic structures of Au and Ag films epitaxlly grown on the InP(001) -p(2×4), which have been characterized by means of LEED, RHEED, AES and RBS-channeling.

2. Experiments

The InP specimen used was a (001)-oriented, n-type and undoped single-crystalline wafer (Showa Electric Industries Ltd.). The specimen surface was mechanically polished, cleaned in standard solvents, etched in a H_2O:$8H_2SO_4$ solution for 1 min at 60°C and in a H_2O:NH_4F solution for 1 min at room temperature and finally cleaned in deionized water. The specimen was mounted on a three-axes rotatable goniometer with two-axes linear motion having an angular resolution of 0.025° in a conventional UHV chamber which was connected to a differentially pumped beam line of a 2.0MeV van de Graaff accelerator, and in which a base pressure no more than 4×10^{-10} Torr was regularly achieved. The specimen surface was cleaned by repeating 0.5 keV Ar^+ sputtering for 20 min at a current density of 0.1μA/cm^2 and subsequent annealing at 300°C for 10 min so that clear LEED spots of p(2×4) could be observed, as shown later. Hereafter, the Au or Ag films with different thickness were deposited on the substrate at room temperature, keeping a pressure less than 4×10^{-9} Torr at a deposition rate of 3Å/min.

At each stage of the surface cleaning and deposition, the specimen surface was observed in-situ by means of the LEED, (or RHEED), AES and RBS-channeling techniques. The RBS-channeling measurement was performed with a 1.5 MeV He^+ ion beam of 1 mm in diameter which was incident along the <001> direction of the InP substrate.

3. Experimental results and discussion

First of all, the results on LEED or RHEED observation are described. A LEED pattern of p(2×4) spots was observed for a cleaned InP(001) surface and a LEED pattern was observed for a Au film, of 20 Å in thickness, deposited onto the cleaned surface. The p(2×4) pattern (a) corresponds to the most commonly observed surface structure of the cleaned InP(001) surface which is modeled by the missing row dimer structure [9]. The p(1×1) pattern for the Au film corresponds to the c(2×2) pattern for the Au (001) face, as explained later. The result indicates that the Au single-crystalline film grows epitaxially along the <001> direction on the InP(001) surface only by room temperature deposition.

RHEED patterns observed for a Ag film, of 15.8 Å in thickness, deposited onto the InP(001) surface are shown in Fig.1, where the RHEED patterns for a cleaned InP(001) surface are also shown. The RHEED patterns (a) and (c) were observed for the case of the electron beam incident along the <110> direction of the InP (001) surface and the RHEED patterns (b) and (d) along the <101>. One can see that the RHEED patterns (c) and (d) for the Ag film do not show the reflection diffraction rods, but the transmission diffraction spots, which indicate that the Ag film deposited at room temperature grows in the Stranski-Krastanov (S-K) mode. Since Ag is a face-centered cubic lattice, the
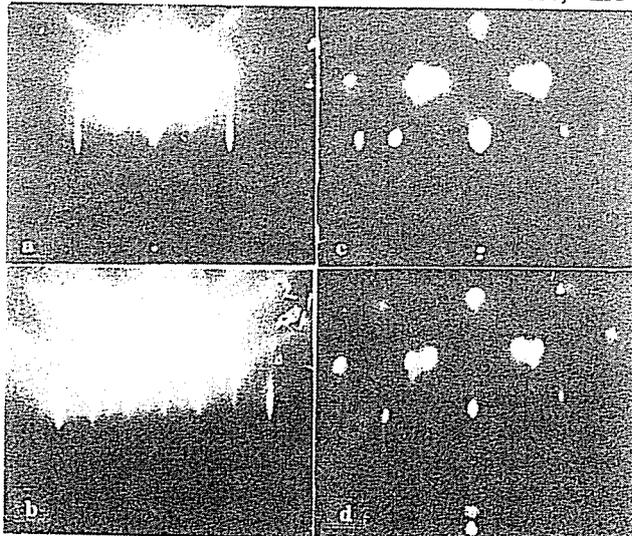
Fig.1 RHEED patterns(a) and (b) from a InP(001)-p(2×4) surface which correspond to the 4 and 2 times superlattice, respectively and (c) and (d) from a Ag film of 15.8 Å in thickness deposited on the InP(001)-p(2×4) surface at room temperature. The directions of the incident electron beam for (c) and (d) correspond to those for (a) and (b), respectively.

RHEED patterns (c) and (d) turn out to be a superposition of transmission diffraction spots for the (110) and (001) faces of the Ag crystal, to which the direction of the electron beam is perpendicular. This result indicates that the Ag film grows along the <110> direction on the InP(001) surface. The <110> growth of Ag is quite different from the <100> growth of Au describe above.

Next, we discuss the orientation of the epitaxially grown film against the InP substrate. The atomic arrangements of the (001) face of fcc Au and of the (001) face of fcc InP are shown in Fig.2 and those of the (011) face of fcc Ag and of (001) face of fcc InP in Fig.3. In Fig.2, the unit cell of Au is rotated azimathully 45° with respect to the InP unit cell. It is seen from Fig.2 that the Au spacing is 1.7 % smaller than the In spacing. This indicates that the <001> epitaxial growth of Au is very reasonable. It is also clearly seen from Fig.2 that a LEED pattern of p(1×1) spots for the InP(001) lattice is reduced to c(2×2) spots for the Au (001) lattice by lateral displacement of single atom or pair atoms in the Au unit cell.

It is seen from Fig.3 that the mismatch of 3 times the Ag atomic spacing in the <110> direction to 2 times the In atomic spacing in the <110>direction is 4.7 % and the mismatch of the Ag atomic spacing in the <100> direction to the In atomic spacing in the <110> direction is 1.1 %. It is also clearly seen from Fig.1 that in (c) the brightness of (1,0) and (-1,0) spots for the (110) face is stronger than that for the (001) face, while in (d) the brightness of (1,0) and (-1,0) spots is weaker. The transposition of the brightness between the two spots in (c) and (d) indicates that the <100> direction of the Ag (110) crystalline prefers to orient along the <110> direction of 4 times super lattice of the InP(001)-p(2×4) surface. This preferential orientation of the Ag crystallites may be ascribed to the mismatch between the atomic spacings in Ag and InP lattice. However, the reason why the orientation of the epitaxial growth of Ag is different from that of Au is not understood yet.

The crystalline quality of epitaxially grown films of Au and Ag was investigated by means of the RBS channeling measurement of 1.5 MeV He$^+$ ion beam along the <001> direction of the InP(001) substrate. Typical RBS spectra of 1.5 MeV He$^+$ ion beam from the Au film of 20 Å in thickness deposited on the InP(001) substrate are shown in Fig.4, where open and closed circles represent the random and aligned spectrum in the <00$\bar{1}$> axial direction of

4.08 Å

4.08 Å

[010]

[100]

Au(001) lattice

(◯ : 1st layer,   ○ : 2nd layer)

8.68 Å

4.09 Å

[100]

[0̄11]

Ag(011) lattice

(◯ : 1st layer,   ○ : 2nd layer)

4.15 Å

4.15 Å

5.87 Å

[110]

[101]

In lattice in InP(0̄01)

(△ : 1st layer, △ : 3rd layer, □: P)

8.30 Å

4.15 Å

5.87 Å

[110]

[101]

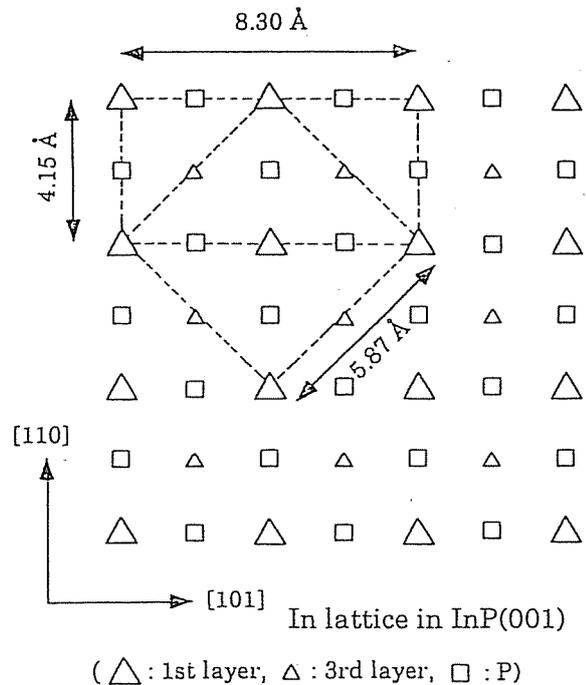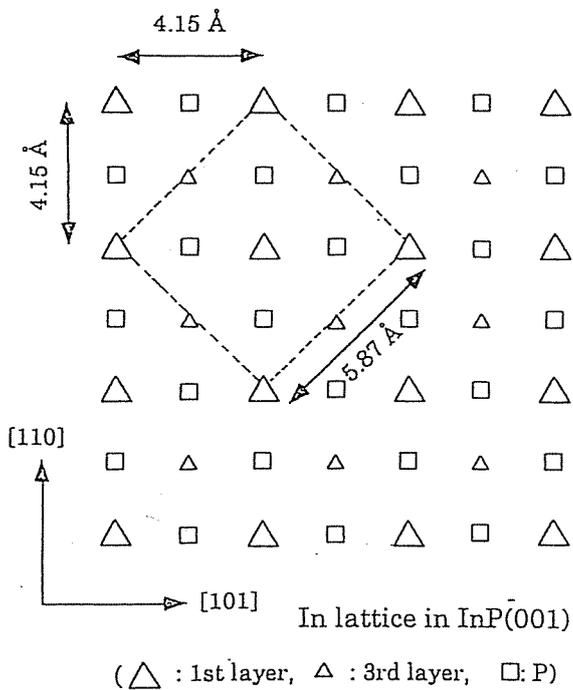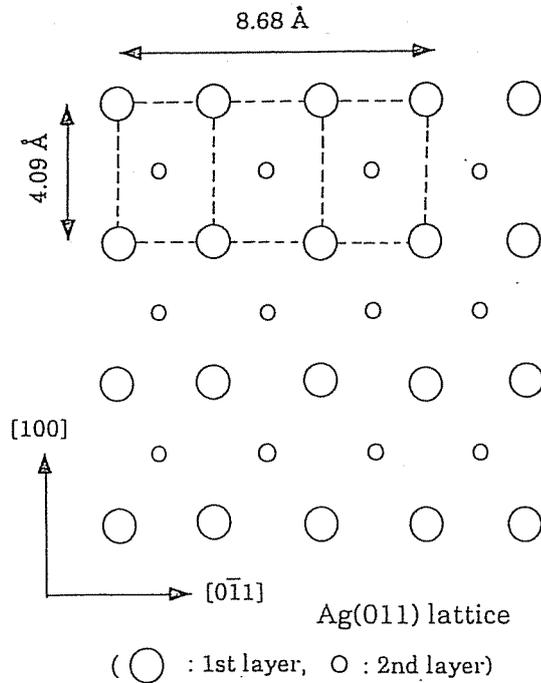In lattice in InP(001)
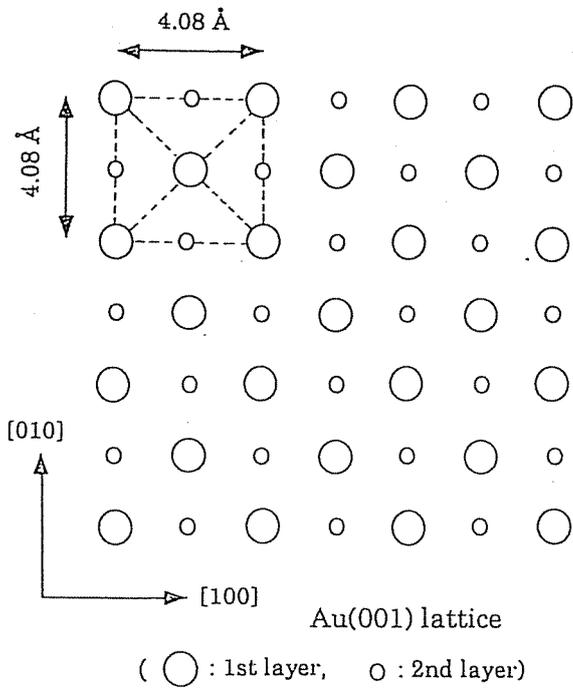
(△ : 1st layer, △ : 3rd layer, □ : P)

Fig.2 Schematic illustration of atomic arrangements for a Au(001) face and for an InP(001) face. The unit cell of Au is rotated azimuthally 45° with respective to the InP unit cell.

Fig.3 Schematic illustration of atomic arrangements for a Ag(011) face and for an InP(001) face.
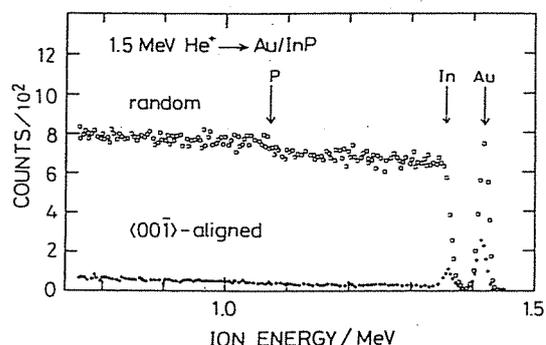
Fig,4 RBS spectra of 1.5 MeV He$^+$ ions from the Au layer deposited on the InP(001) substrate at room temperature:(○) for random direction and (●) for the <00$\bar{1}$> channeling direction of the InP substrate.

the InP(001) substrate, respectively. It is clearly seen from Fig.4 that the aligned yield of the Au film is considerably reduced compared with the random yield. From the ratio of the aligned to random yield, it was estimated that the average minimum yield for the Au film was 32.5%. The average minimum yield for the Ag film of 20.7 Å in thickness was found to be 36 %. The large minimum yields are explained quantatively well in terms of thinness of their films by taking into account the thermal lattice vibration. The result indicates that the crystalline quality of expitaxially grown films of Au and Ag is excellent.

The channeling minimum yield for the Au film of 20 Å thick was numerically calculated by taking into account the displacement of single atom and pair atoms in the Au unit cell of the (001) face and the thermal lattice vibration. It was determined from comparison between the experimental and calculated minimum yield that the atomic arrangement of Au atoms in the Au(001) unit cell lateral of c(2×2) is a pair atoms displacement and the lateral displacement of Au atoms is 0.18 Å.

Acknowledgements

References
1) H. B. Kim, A. F. Lovas, G. G. Sweeney and T. M. S. Heng. Inst. Phys. Conf. Ser. Vol. 33b, 145(1977)
2) B. Tuck, K. P. Ip and L. F. Eastman, Thin Solid Films Vol. 55, 41(1978)
3) N. SSzzyllo and J. Oliver, J. Appl. Phys. Vol. 50,1445(1975)
4) A. Hiraki, K. Shuto, S. Kim, W. Kammura and M. Iwami, Appl. Phys. Lett. Vol. 31, 611(1977)
5) P. W. Chye, L. Lindau, P. Pianetta, C. M. Garner, S. Y. Su and W. E. Spicer. Phys. Rev. Vol. B18, 5545(1978)
6) M. Renda and K. Morita, Appl. Surf. Sci. Vol. 41/42,216(1989)
7) T. Katoh and K. Morita, Appl. Surf. Sci. Vol. 56-58, 199(1992); Vol. 56-58, 185(1992)
8) M. Hanebuchi, T. Katoh and K. Morita, Appl. Surf. Sci. (1995) in print.
9) X. Hou, G. Dong, X. Ding and X. Wang, J. Phys. Vol. C20, L121(1980)