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Characterization of Au thin films deposited on α-Sn(1 1 1)-(3 × 3)/InSb(1 1 1)A surfaces

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Abstract

For the purpose to elucidate the character of the interface between Au metal and α-Sn films, Au metal thin films deposited on α-Sn(1 1 1) surfaces grown on InSb(1 1 1)A substrates are examined by using reflection high-energy electron diffraction (RHEED). The (1 1 1) surface of the α-Sn film with only the 3 × 3 reconstruction grown at 50 °C is used as a well-defined α-Sn(1 1 1) substrate for the growth of Au films. NiAs-type AuSn films with a high crystallinity are grown in the 1.1-nm-thick Au-deposited thin films on the α-Sn(1 1 1) held at room temperature (RT). The NiAs-type AuSn films have a 2 × 2 reconstructed surface structure. The orientation relationships between the AuSn and the α-Sn films are (0 0 1) AuSn//(1 1 1) α-Sn and [2 1 0]AuSn//[2 $\bar{1}$ $\bar{1}$] α-Sn. On the other hand, at 60 °C, the AuSn with a high crystallinity grows in Au-deposited films of about 2.8 nm in thickness, although at RT the AuSn with a high crystallinity grows in Au-deposited films of about 1.1 nm in thickness as stated above. The difference of Au-deposited film thickness between them results from the difference of their interdiffusion lengths of Au and Sn atoms, which depend on the temperature. Taking the interdiffusion into account, the properties and the formation mechanism of interfaces between Au metal thin films as an electrode and the α-Sn/InSb semiconductor superlattice are discussed.

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1. Introduction

The properties of the interfaces between electrode metal thin films and the semiconductor superlattices are quite interesting, due to their promising application as high electron mobility transistors and semiconductor laser devices. An Au metal film grown on α-Sn/InSb surfaces is one of such systems [1,2]. Understanding the properties of interface between the electrode Au metal thin film and the α-Sn/InSb semiconductor superlattice will play an important role in improving the reliability of semiconductor quantum devices (for example, infrared absorption devices). In order to examine the interface between the Au thin film and the α-Sn/InSb semiconductor superlattice, atomically flat and clean surfaces of α-Sn thin films with a well-defined surface structure have to be prepared on InSb substrates that have a wider band gap than α-Sn. Although the bulk Sn is known to have a semiconducting α-phase with a diamond structure and an identically zero gap at temperature below 13.2 °C, and to have a metallic β-phase with a tetragonal structure above this temperature, Sn films grown on InSb substrates are reported to have an α-phase even above room temperature (RT) [2–7]. The (1 1 1) surface of the α-Sn film grown on an InSb(1 1 1)A-(2 × 2) was reported to show different surface reconstructions depending on the cleaning methods of the substrate [5]. That is, 3 × 3 and 2 × 2 reconstructions of the α-Sn(1 1 1) surface were observed on the cleaned InSb(1 1 1)A surface prepared by using the molecular beam epitaxy (MBE) method [3,5], while only a 1 × 1 reconstruction was observed in the case of cleaning by repeated sputtering

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and annealing [2,4,6,7]. It was reported that this difference cannot result from the diffusion of In atoms into the Sn overlayer, and that, taking into account that the 3×3 and 2×2 reconstructions observed at lower temperature transformed into a 1×1 structure at higher temperatures [5], one possible explanation is the disordering of the surface Sn atoms, which can be produced by the presence of only small 3×3 and 2×2 domains, whose phases are shifted [4]. These small Sn domains could be induced by the repetition of sputtering and annealing. It was also reported that the 2×2 reconstruction was observed in the transition processes from the 3×3 reconstruction of as-grown α-Sn film surface to the 1×1 structure during heating of the α-Sn film [5]. Thus, in this paper, the (1 1 1) surface of the α-Sn film with only the 3×3 reconstruction is used as a well-defined α-Sn(1 1 1) surface. The detailed growth processes of Au films on a well-defined α-Sn(1 1 1) surface with the 3×3 reconstruction prepared by using the MBE method have not yet been investigated.

In this paper, Au metal thin films deposited on α-Sn(1 1 1) surfaces grown on InSb(1 1 1)A are examined by using reflection high-energy electron diffraction (RHEED) for the purpose to elucidate the structural properties of the interface between the Au metal and the α-Sn films.

2. Experimental procedure

The experiment was performed in the MBE system equipped with RHEED, which was evacuated by a turbomolecular pump and an ion pump system. The ultimate pressure and the pressure during deposition of Sn and Au were, after activating the liquid N_2-cooled baffles in the vicinity of the evaporation sources, 1×10^{-10} and 6×10^{-10}–1×10^{-9} Torr, respectively. The substrates were chemically polished before being loaded into the evaporation chamber. First, the substrates were rinsed in trichloroethylene and ethanol, three times repeatedly, and were then etched in a lactic acid (LA)–HNO_3 (10:1) solution for 1 h. Immediately after the chemical polishing, the substrate was mounted onto the molybdenum heating block attached to the sample holder in the MBE chamber.

The first cleaning treatment of the substrate surface in the MBE system was performed by heating for 20 min at 460 °C with Sb_4 beams [3,5,8], which were evaporated from an effusion cell of Ta, impinging onto the substrate at a rate of 3.8×10^{16} (atoms/(m^2 s)). The second treatment was as follows: Molecular beams of In_1 and Sb_4 were impinged on InSb(1 1 1)A substrates at 330 °C with fluxes of In_1 (4.8×10^{16} (atoms/(m^2 s))) and Sb_4 (5.5×10^{16} (atoms/(m^2 s))). The sources of In_1 and Sb_4 beams were effusion cells composed of high-purity Ta thin plates. Finally, the InSb substrate was annealed for 20 min at 400 °C. After the thermal cleaning treatments, the substrate was cooled down to RT at a rate of 3 °C/min. Atoms of Sn and Au were, respectively, deposited from each W-basket onto the substrate at a rate of 0.1 nm/min. The deposition rate and film thickness were monitored with a quartz crystal microbalance. All RHEED patterns were observed at an accelerating potential of 20 keV and were recorded by a CCD camera–video system. The substrate temperatures were measured by a chromel–alumel thermocouple and were calibrated by melting the InSb substrate at a temperature of 525 °C, corresponding to the bulk melting point.

3. Results and discussion

It was confirmed by RHEED observations performed along $[2\bar{1}\bar{1}]$ and $[01\bar{1}]$ azimuths of the thermally cleaned InSb(1 1 1)A substrate prepared by a MBE method that the thermally cleaned InSb(1 1 1)A surface (lattice constant: $a = 0.64798$ nm) has a 2×2 reconstructed structure [3,5,9–11]. Figs. 1(a) and (b) show typical RHEED patterns taken along the $[2\bar{1}\bar{1}]$ and $[01\bar{1}]$ azimuths of 2.0-nm-thick α-Sn(1 1 1) surface grown on InSb(1 1 1)A-(2×2) substrates at 50 °C by a MBE method, respectively. An analysis of fundamental reflections marked by large arrows and reflections marked by small arrows in Fig. 1 indicates that the α-Sn(1 1 1) surface (lattice constant: $a = 0.6489$ nm) grown on InSb(1 1 1)A-(2×2) at 50 °C has a 3×3 reconstructed structure [3,5]. The results of RHEED observations of α-Sn(1 1 1) surface grown on InSb(1 1 1)A-(2×2) substrates at RT were similar to those of α-Sn(1 1 1) surface grown at 50 °C, although the diffraction pattern of the latter was sharper than that of the former, which meant that the crystallinity of α-Sn(1 1 1) surface grown at 50 °C was better than that grown at RT. Taking account of the better crystallinity of α-Sn(1 1 1) surface grown at 50 °C, and of the 3×3 reconstruction of as-grown α-Sn(1 1 1) surface mentioned in Section 1, the (1 1 1) surface of the α-Sn film grown at 50 °C with only the 3×3 reconstruction was used as a well-defined α-Sn(1 1 1) substrate for the growth of Au films.

Fig. 2 shows a series of RHEED patterns of Au-deposited thin films on α-Sn(1 1 1) held at RT as a function of deposited film thickness of Au, taken along the $[01\bar{1}]$ azimuth of α-Sn(1 1 1) surface; (a) as-grown α-Sn(1 1 1), (b) 0.2 nm, (c) 0.4 nm, (d) 1.2 nm, and (e) 3.0 nm. The $\frac{1}{3}$ order reflections indicated by small arrows in Fig. 2(a) disappeared at the Au-deposited film thickness of 0.2 nm in Fig. 2(b), while the weak $\frac{1}{2}$ order reflection indicated by a small arrow in Fig. 2(b) was observed. As can be seen from Figs. 2(c) and (d), the $\frac{1}{2}$ order reflection indicated by a small arrow becomes stronger with the increase in the Au-deposited film thickness up to about 1.2 nm. In case of the thicker Au-deposited film than 1.2 nm, the $\frac{1}{2}$ order reflection becomes weaker with the increase in the film thickness. At the Au-deposited film thickness of 3.0 nm in Fig. 2(e), it is difficult to observe the $\frac{1}{2}$ order reflection and the fundamental reflections become weaker as indicated by a large arrow. These results mean that for the thicker Au-deposited film than about 1.2 nm, the disordered area increases gradually with the film thickness.