Spin-polarized surface states localized in subsurface layers of Pb/Ge(111)

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1. Introduction

Spin-orbit interaction is believed to play a decisive role in coming spintronic devices that do not need ferromagnets or external magnetic field and hence are highly compatible with the existing semiconductor-based electronics. Among the phenomena related to the spin-orbit interaction, the Rashba effect refers to the spin splitting of two-dimensional electronic states induced by the structural inversion asymmetry at, for instance, semiconductor heterojunctions. Here, the Rashba effect at solid surfaces has been attracting significant interests because the size of the spin splitting is orders of magnitude larger than those in the semiconductor heterojunctions. Most of the known surface Rashba systems were based on the surfaces containing heavy element atoms so far [1-4]. On the other hand, very recently, we have discovered the spin-polarized surface states localized in subsurface layers of the Ge substrate on Br/Ge(111), Tl/Ge(111) and Bi/Ge(111) due to the surface Rashba effect [5-7]. In the present study, we report that such spin-polarized surface states are also formed in one-monolayer Pb adsorbed Ge(111) (Pb/Ge(111)-β) system.

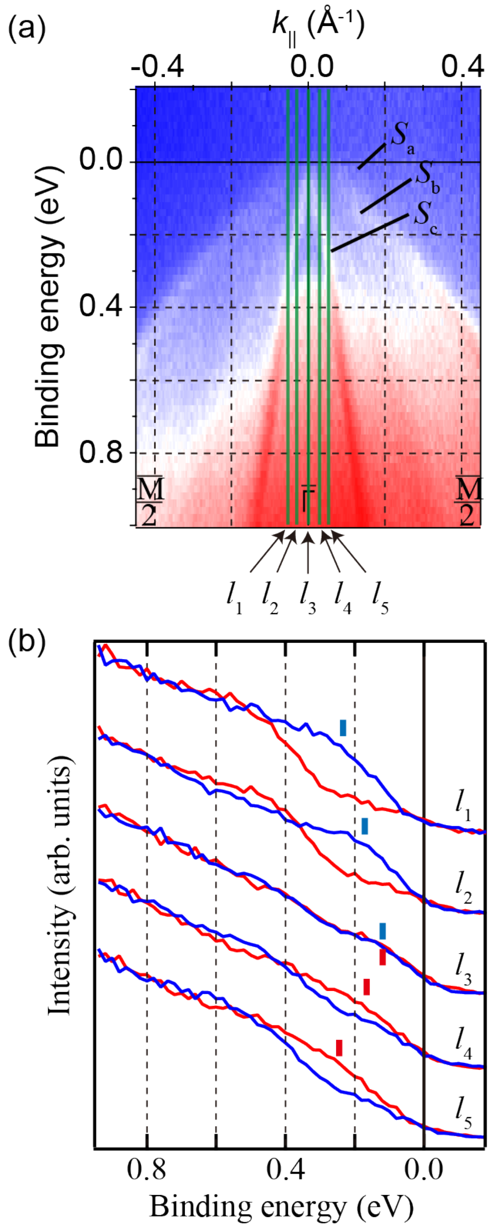

Figure (a) ARPES image of Pb/Ge(111)-β taken with the photon energy of 25 eV. (b) SARPES spectra taken along thin solid (green) lines, l_1-l_4, shown in (a). Red and blue lines represent the up and down spin states, respectively.

2. Experimental methods

Angle-resolved photoelectron spectroscopy (ARPES) and spin- and angle-resolved photoelectron spectroscopy (SARPES) experiments were performed at BL-19A of Photon Factory, KEK. An electron energy analyzer with very low energy electron diffraction type spin polarimeter was used for SARPES. The sample temperature was maintained at room temperature during the measurements. An *n*-type Ge(111) substrate was prepared by several cycles of Ar^+ bombardment with 0.5 kV and annealing up to 900 K for a minute, which gave a good *c*(2×8) low-energy electron diffraction (LEED) pattern. Pb was deposited onto the surface at room temperature from an alumina crucible heated with a tungsten filament. The surface after the Pb deposition was annealed at 570 K for three minutes to prepare a well-ordered wide terrace of Pb/Ge(111)-β.

3. Results and discussion

Figure (a) shows an ARPES image recorded with the photon energy of $h\nu$ = 25 eV along $\bar{\Gamma}$ $\bar{M}$ direction of (√3×√3)R30° surface Brillouin zone. We found three Ge-derived bands named S_a, S_b and S_c, where the bands disperse near the projected bulk band edges. These bands show no photon energy dependence, indicating that S_a–S_c are surface states and surface resonances. The shapes of the band structures are quite similar to that observed in Bi/Ge(111) [5] and Br/Ge(111) [6] except for band energies. We note that the S_a band of Pb/Ge(111)-β crosses the Fermi level, indicating that S_a is metallic. The spin structures were investigated by SARPES, shown in Fig. (b). The red and blue spectra represent spin-up and spin-down states, respectively. Here, the spin-polarized S_c band is clearly observed with SARPES. We first recognize that spin-up and spin-down states are degenerate at $\bar{\Gamma}$. Next, the spin-down states are found with the wave vector cuts of l_1 and l_2. On the other hand, the spin-up states are prominent for l_4 and l_5. The peak positions of the spin-up and spin-down of S_c are thus inverted with respect to $\bar{\Gamma}$. We therefore conclude that the S_c band shows the Rashba-type spin structure. Our findings clearly show that the significant spin polarization of the surface state bands of semiconductor can be obtained.

4. Summary

We have studied the electronic band structure of Pb/Ge(111)-β near the Fermi level around $\bar{\Gamma}$ by means of ARPES and SARPES. We found three Ge-derived surface states and surface resonances with ARPES. The SARPES measurements revealed that the surface states are spin-polarized due to the Rashba effect. Similar spin-polarized states were also found in other systems, such as Bi/Ge(111), Tl/Ge(111) and Br/Ge(111). We believe that the formation of the spin-polarized surface states localized in subsurface layers is the universal nature of a Ge subsurface region.

References

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