# Giant Rashba spin splitting on monolayer-Pb-covered Ge(111) surface

Koichiro Yaji[1,2], Akito Kakizaki[1], and Tetsuya Aruga[2,3]

[1]*Institute for Solid State Physics, The University of Tokyo, Kashiwa, Chiba 277-8581, Japan*

[2]*JST CREST, Saitama 332-0012, Japan.*

[3]*Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan.*

## 1. Introduction

Rashba spin splitting of a surface state band on a semiconductor surface allows us to open a novel physics such as a spin transport at the surface. The Rashba spin-split bands on the semiconductor surfaces have been identified on Si(111) and Ge(111) surfaces so far [1-4]. Among them, monolayer lead (Pb) covered Ge(111) surface (Pb/Ge(111)-β) is remarkable because one of the surface state bands crosses Fermi level with the Rashba spin splitting [4]. We have pointed out that the Pb/Ge(111)-β surface can become an ideal prototype for the spin transport study. On the other hand, the spin structures of the other surface-state bands are unclear. In the present article, we report on a giant Rashba spin-split band of Pb/Ge(111)-β near the $\bar{M}$ point measured with angle-resolved photoelectron spectroscopy (ARPES) and spin- and angle-resolved photoelectron spectroscopy (SARPES).

## 2. Experimental methods

A Ge(111) substrate was prepared by several cycles of 0.5-keV $Ar^+$ bombardment and annealing up to 900 K for a minute. Clean surface of Ge(111) was checked by observing a sharp (2×8) LEED pattern. Pb was deposited onto the surface at room temperature from an alumina crucible heated with a tungsten filament. The surface was then annealed at 570 K for three minutes to prepare a well-ordered wide terrace of Pb/Ge(111) with $(\sqrt{3}\times\sqrt{3})R30°$ periodicity. The Pb coverage of Pb/Ge(111)-β was checked by an intensity ratio between Ge 3*d* and Pb $5d_{5/2}$ core-level spectra, a full-width at half-maximum of the Pb $5d_{5/2}$ core level spectra, and the observation of the sharp $(\sqrt{3}\times\sqrt{3})R30°$ LEED pattern. ARPES and SARPES were performed at BL19A in Photon Factory. The sample temperature was set to room temperature during the measurements.

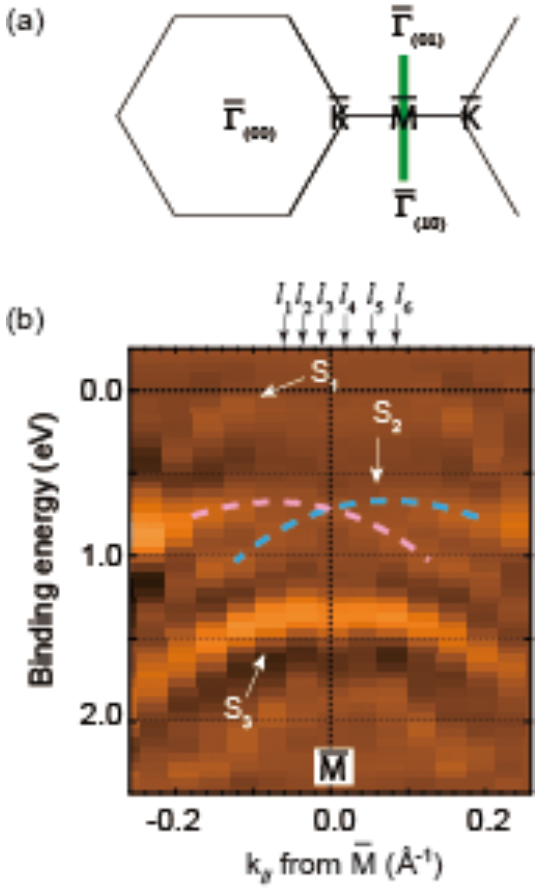


Fig. 1 (a) SBZ of Pb/Ge(111)-β. (b) ARPES image taken along green line in the SBZ shown in (a). Dashed curves represent two branches of $S_2$.

## 3. Results and discussion

Figure 1(b) shows the ARPES image taken along $\bar{\Gamma}\ \bar{M}\ \bar{\Gamma}$ of $(\sqrt{3}\times\sqrt{3})R30°$ surface Brillouin zone (SBZ) shown in Fig. 1(a). The photon energy ($h\nu$) was set to 21 eV. We

found three Pb-induced bands named $S_1$, $S_2$ and $S_3$. These bands were also observed with $h\nu$ = 25, 30 eV. This indicates that $S_1$, $S_2$ and $S_3$ are surely surface states or surface resonances. The $S_1$ band, which shows *free-electron-like* metallic feature, splits into two due to the Rashba effect [4]. The $S_2$ and $S_3$ bands are surface resonances because the states appear within the projection of Ge bulk bands. In Fig. 2, the SARPES spectra taken at k points shown by the arrows in Fig. 1(b) are shown. The red and blue spectra represent spin-up and spin-down states, respectively. We found that the spin-up and spin-down branches of $S_2$ are degenerate at the $\bar{M}$ point. The peaks of $S_2$ show the spin splitting at k points away from $\bar{M}$. The peak positions of the spin-up and spin-down branches are inverted around $\bar{M}$. We therefore conclude that the $S_2$ band splits into two due to the surface Rashba effect. The Rashba parameter is roughly evaluated to be 1.9 eV Å, which is comparable with the other giant Rashba systems [1-3]. On the other hand, we could not observe the Rashba spin splitting of $S_3$ because the intensity of the spin-down state of $S_3$ is always larger than that of the spin-up state even at $\bar{M}$.

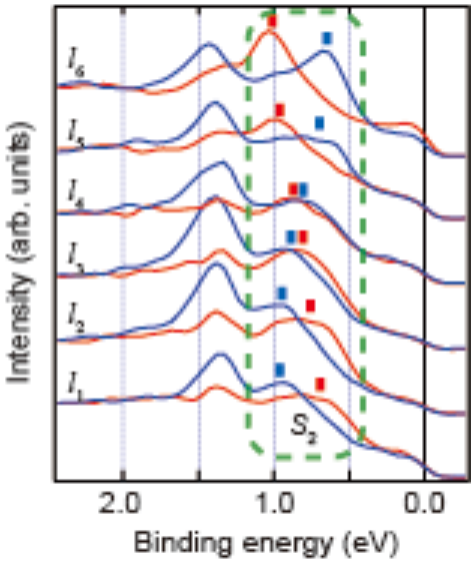

Fig. 2 SARPES spectra taken with the arrows shown in (b). Red and blue lines represent the up and down spin states, respectively.

We found that Pb/Ge(111)-β exhibits the giant Rashba spin-split band around $\bar{M}$. Similar surface-state bands with the giant Rashba spin splitting around $\bar{M}$ have been identified on Bi adsorbed Si(111) and Ge(111) surfaces [1-3]. Here, the Rashba spin-split bands of Bi/Si(111) and Bi/Ge(111) are ascribed to the bonding orbitals between the Bi atoms near the $T_1$ sites and the Si (Ge) atoms in the topmost layer of the substrates. Concerning Pb/Ge(111)-β, there are two positions for the Pb adsorption in the unit cell, where one Pb atom is located at an $H_3$ site and three Pb atoms are located near the $T_1$ sites. The Pb atoms near the $T_1$ sites and the Ge atoms in the topmost layer make the Pb-Ge bonding orbitals, which is the origin of the $S_2$ band [5]. This hybridization can produce the strong perpendicular asymmetry of the wave function, which explains the giant Rashba effect around $\bar{M}$ of Pb/Ge(111)-β. The resemblance of the local adsorption geometries at $T_1$ and the hybridization between the adsorbates and the substrates may explain the similar giant Rashba spin splitting in Bi/Si(111), Bi/Ge(111) and Pb/Ge(111)-β.

## 4. Summary

We have studied the electronic structure of Pb/Ge(111)-β by ARPES and SARPES. We found the surface-state band ($S_2$) with the giant Rashba spin splitting around $\bar{M}$. The Rashba parameter is evaluated to be 1.9 eV Å, which is comparable with the other giant Rashba systems such as Bi/Si(111) and Bi/Ge(111). Also, the feature of the giant Rashba band for Pb/Ge(111)-β is similar to those for Bi/Si(111) and Bi/Ge(111). The resemblance comes from the similar local adsorption geometries at $T_1$ sites and the characters of the bands.

## [References]


[1] I. Gierz *et al.*, PRL **103**, 046803 (2009).
[2] S. Hatta *et al.*, PRB **80**, 113309 (2009).
[3] K. Sakamoto *et al.*, PRL **103**, 156801 (2009).
[4] K. Yaji *et al.*, Nature. Commun. **1**, 17 (2010).
[5] K. Yaji *et al.*, *unpublished*.