In-plane Dispersion of Valence Subbands in Si Inversion Layer Visualized by Angle-Resolved Photoelectron Spectroscopy

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In-plane dispersion of the subbands in semiconductor quantum well is essential to understand the transport properties of the confined electrons or holes. The dispersion structure of the subbands is no more same as the bulk semiconductor. Especially, valence subband has complicated structure due to the coupling of the heavy-hole (HH) and light-hole (LH) states. Although there are several theoretical studies on the dispersion structure of the valence subbands, experimental approach is rare.

We introduced Angle-resolved photoelectron spectroscopy (ARPES) to obtain the dispersion structure of the valence subbands. ARPES is a powerful tool to directly probe the electronic structure of solids and has been used to observe the electronic structure of various materials. In the ARPES experiment, we irradiate the sample surface by mono-energetic photons and detect the emitted photoelectrons analyzing their kinetic energy and emission angle. From the kinetic energy and emission angle, binding energy and momentum which photoelectrons had in the sample are obtained. Because the probing depth of ARPES is about 10-20Å beneath the sample surface, which is determined by photoelectron escape depth, quantized states should be formed there to utilize ARPES. Additionally, we can not use insulators such as SiO_2 because the kinetic energy of the photoelectrons is seriously modified by the charge-up effect. So, we made confinement potential using band bending by metal adsorption on the surface. Metal adsorbed on the semiconductor surface often forms ordered structure called surface structure. The electronic states of the surface structure accommodate surface charge which causes band bending.
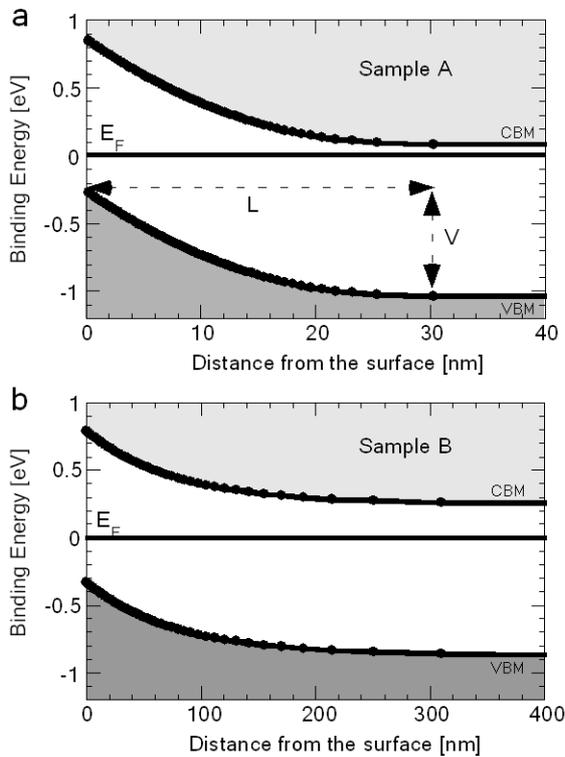
Fig.1. Calculated shapes of the Inversion layer for sample A and sample B.
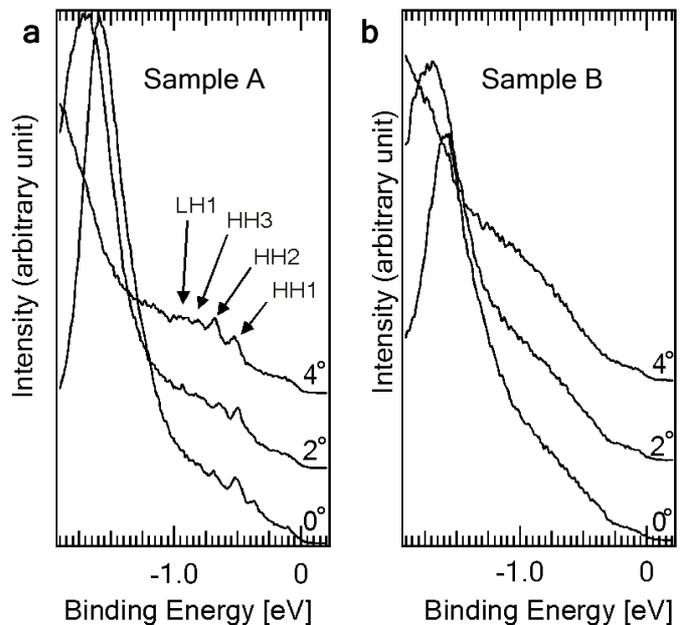
Fig.2. Photoelectron spectra from sample A and sample B at room temperature. The emission angle of the photoelectron denoted on each spectrum is scanned along [11$\bar{2}$] direction.

We prepared p-type inversion layer in n-type Si(111) surface using Indium surface structure known as Si(111)$\sqrt{7}\times\sqrt{3}$ -In, which consists of one monolayer of Indium. This surface structure has acceptor-type surface electronic states and makes upward band-bending. By using the high-doped (1×10^{18}cm^3, named sample A) and low-doped (1×10^{15}cm^3, named sample B) Si(111) substrates, we made two kinds of inversion layers as shown Fig.1. The main difference of sample A and B is the width W of the space charge layer. The width W for sample A is 30nm, which is much shorter than sample B (300nm). All experiments were done in an ultra-high-vacuum chamber to prevent the surface contamination.

The photoelectron spectra from sample A at room temperature clearly detected the subbands which are seen as peaks HH1, HH2, HH3 and LH1 in fig.2a. On the other hand, photoelectron spectra from sample B have no clear peaks of the subbands. These results were in good agreement with results of the calculation using the triangle approximation. The detailed ARPES measurements visualized the subband dispersion in sample A. Figure 3 shows the second derivative intensity map of the photoelectron in E_B - $k_{//}$ form with in-plane wave number $k_{//}$ along

[11$\bar{2}$] direction. Crossings or repulsions of the subbands occur at the $k_{//} \sim 0.5$Å. Negative effective masses around $k_{//} = 0$ for the bands Γ_2 and Γ_3 were clearly observed. At the large momentum region, the dispersions of each subband were similar to the respective bulk valence bands.

The application of ARPES to subband dispersion was demonstrated in this study. Further information will be obtained from the low temperature measurements.
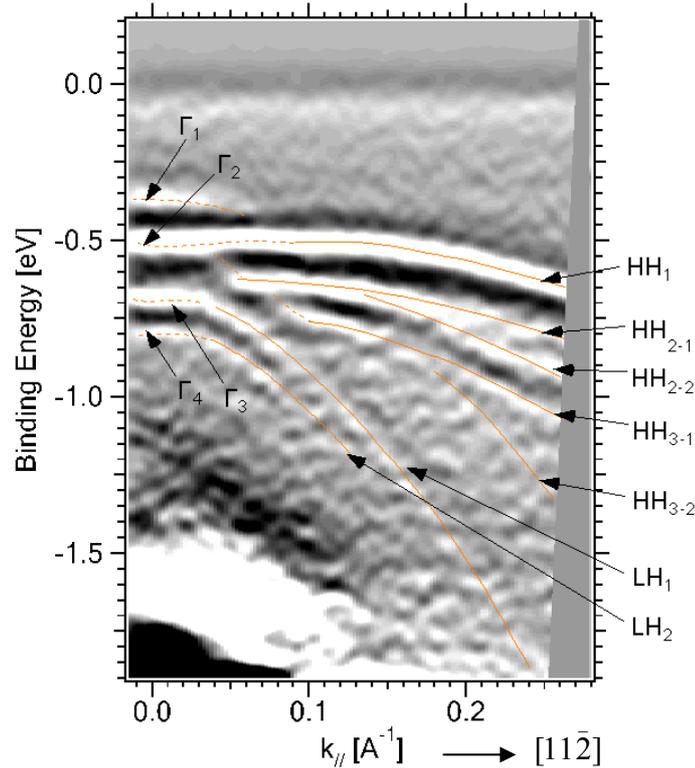
Fig.3   Second derivative intensity map of the photoelectron from sample A. Bright area corresponds to the electronic states. The horizontal axis is in-plane momentum $k_{//}$ converted from the photoelectron emission angle θ using the relation $k_{//} = \dfrac{\sqrt{2m}}{\hbar}\sqrt{E_{kin}}\sin\theta$ where E_{kin} is the kinetic energy of the photoelectron.