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MODIFICATION OF ELECTRONIC STATES OF √3×√3-Ag STRUCTURE BY STRAINED Ge/Si(111) SUBSTRATE

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Introduction

Much interest has been attracted on a microscopic lattice strain, because it has a large possibility to design nanoscale properties. The electronic state of the nanostructure depends on its structure involving the lattice strain to stabilize the nanostructure. To make clear the relation between electronic states and strain in nanoscale, the study in two-dimensional system is very useful and the results will give possibilities for nano-electronics applications.

We focus on the quasi two-dimensional electron gas (2DEG) state formed on the √3×√3-Ag structure, which is typically reconstructed by Ag adsorption (1 ML) on the Si(111) or the Ge(111) [1,2], because the dispersion of the 2DEG state could be modified with the lattice strain introduced by hetero-epitaxial growth such as the Ge/Si(111) or the Si/Ge(111). The compressive strain will be induced to the surface layer by the epitaxial growth of the Ge on the Si(111), and the expansive strain will be induced by the growth of the Si on the Ge(111).

We investigated that the electronic states of the compressive √3×√3-Ag structure on the Ge/Si(111) at several amounts of the Ge coverage (θ_G) measured with a scanning tunnelling microscope (STM) and an angle resolved ultraviolet photoelectron spectroscopy (ARUPS).

Experimental

The STM observations were performed in our laboratory (U-STM, ULVAC), and the ARUPS observations were performed in BL-18A (Institute for Solid State Physics, University of Tokyo). The STM images were taken in the constant-current mode with a tunnel current I_t, of 50 pA and several sample bias voltages V_s, at room temperature (RT). All ARUPS spectra were measured with the polarized light with the photon-energy of 21.2 eV at low temperature (about 120 K). The angular resolution was less than 0.3°, which corresponds to 0.010 Å^{-1} indicated by a wave number, and the energy resolution was less than 0.05 eV.

The strained √3×√3-Ag surfaces were prepared by two step processes: First, the Ge layer was grown on the clean Si(111) substrate, epitaxially, by the evaporation of Ge with θ_G = 0.8 ~ 3.0 BL. To create the Ge(111) 5×5 DAS structure on the epitaxial layer, the substrate temperature T_S was kept at 230 °C during the evaporation, and the sample was annealed (T_A) at 350 °C for 5 min. Under the preparation condition, the Ge atoms are almost staying on the surface rather than intermixing with Si substrate [3]. Second, the Ag was evaporated on the strained Ge layer about 0.5 BL at Ts = RT and T_A = 350 °C for 5 min. After the evaporation, we carried out the STM or the ARUPS observations in each chamber.

Results and discussion

Figures 1(a) and 1(b) show the STM images of the Si(111)-√3×√3-Ag surface and the Ge/Si(111)- √3×√3-Ag surface with θ_G = 1.0 BL (Here after, we abbreviate as S-√3Ag and G-√3Ag, respectively) [4]. These images show a same feature from the honeycomb chained trimer (HCT) structure at RT [5], and we have confirmed that the shape of ARUPS spectra from both surfaces is similar to each other [4]. We conclude that the HCT structure is also formed on the G-√3Ag.

We also find the dispersion of the S_1 state on the G-√3Ag, which is a metallic band crossing the Fermi level, varies depending on θ_G. Figures 2 show gray-scale diagrams of the band dispersion for the S_1 state at (a) θ_G = 0.8 BL, (b) θ_G = 1.0 BL, (c) θ_G = 1.6 BL and (d) θ_G = 3.0 BL, respectively [4], where the second derivative of the EDC is represented by the contrast according to the scale shown in an upper part. Solid circles represent peak positions of the S_1 state determined from the peak fitting with Lorenz functions.

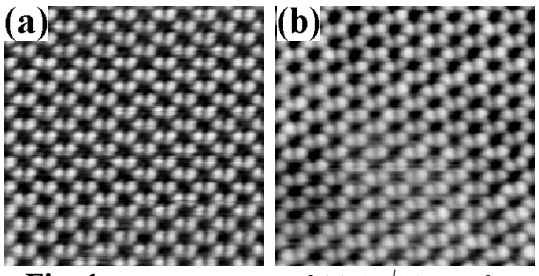

Fig. 1 RT-STM images of (a) S-√3Ag surface and (b) G-√3Ag surface with θ_G = 1.0 BL (8 × 8 nm^2). Both STM images show a typical feature of the HCT structure.

To estimate the lattices strain in each case, we derived the position of $\overline{\Gamma_1}$ point (k_Γ) from fitting with a parabolic function to the dispersion of the S_1 state [4]. The value of k_Γ is estimated from the bottom of the parabola as shown by a vertical solid line, and the dashed line indicates the position of Γ_1 point for the S-√3Ag (1.090 Å^{-1}). Each

value of k_Γ is (a) 1.056 ±0.006 Å^{-1}, (b) 1.076 ±0.005 Å^{-1}, (c) 1.063 ±0.007 Å^{-1} and (d) 1.073 ±0.005 Å^{-1}, which corresponds to the lattice expansion about (a) 3.2 %, (b) 1.3 %, (c) 2.5 % and (d) 1.6 %, respectively. And, we re-examined the curvature of each parabola to estimate the value of the effective mass, m^*. Each calculated value of m^* is (a) 0.28 ±0.03 m_e, (b) 0.19 ±0.02 m_e, (c) 0.30 ±0.03 m_e, and (d) 0.20 ±0.02 m_e, respectively, where m_e is the free electron mass.

When the value of θ_G is integral, k_Γ reaches to the $\overline{\Gamma_1}$ point of the S-√3Ag (1.090 Å^{-1}), the S_1 state disperses steeply and the m^* becomes light. The compressive strain of the G-√3Ag reaches to maximum with the integral value of θ_G. On the other hand, when the value of θ_G is fractional, k_Γ reaches to that of the Ge(111)-√3×√3-Ag surface (1.047 Å^{-1}) and the dispersion becomes gentle. The relationship means that the relaxation of the compressive strain makes the m^* to be heavy.

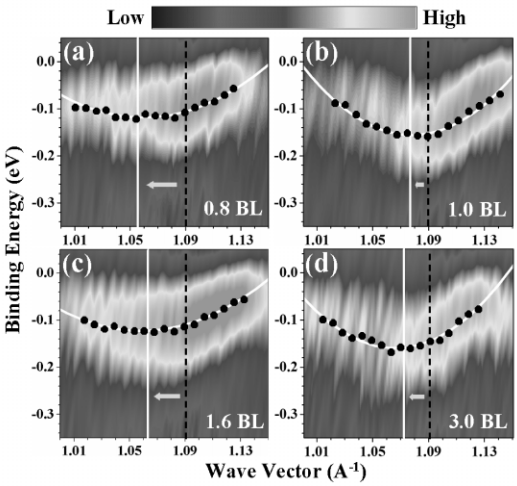

Fig. 2 Gray-scale diagrams of band dispersion for S_1 state at (a) θ_G = 0.8 BL, (b) 1.0 BL, (c) 1.6 BL and (d) 3.0 BL. The solid circle indicates the peak position of S_1 state. The solid curve represents the parabola fitted to the dispersion. The vertical solid line indicates the position of Γ_1 point of the G-√3Ag and the dashed line indicates that of the S-√3Ag.

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