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Surface Science 601 (2007) 1736–1746
SURFACE SCIENCE
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# STM observation of initial growth of Sn atoms on Ge(001) surface

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Received 24 October 2006; accepted for publication 25 January 2007
Available online 4 February 2007

**Abstract**

We have studied initial growth of Sn atoms on Ge(001) surfaces at room temperature and 80 K by scanning tunneling microscopy. For Sn deposition onto the Ge(001) substrate at room temperature, the Sn atoms form two kinds of one-dimensional structures composed of ad-dimers with different alignment, in the ⟨310⟩ and the ⟨110⟩ directions, and epitaxial structures. For Sn deposition onto the substrate at 80 K, the population of the dimer chains aligning in the ⟨310⟩ direction increases. The diffusion barrier of the Sn adatom on the substrate kinetically determines the population of the dimer chain. We propose that the diffusion barrier height depends on surface strain induced by the adatom. The two kinds of dimer chains appearing on the Ge(001) and Si(001) surfaces with adatoms of the group-IV elements are systematically interpreted in terms of the surface strain.


*Keywords:* Scanning tunneling microscopy; Growth; Self-assembly; Surface structure, morphology, roughness, and topography; Germanium; Tin

## 1. Introduction

It is known that group-IV (Si, Ge, Sn, and Pb) and group-III elements (Al, Ga, and In) on Ge(001) and Si(001) surfaces form one-dimensional (1D) structures composed of adatom-dimers (dimer chains) aligning in the ⟨310⟩ or ⟨110⟩ directions at their initial growth stage at room temperature (RT) [1–11]. Their length sometimes exceeds tens of nanometers, while its width is a single-atom size. Thus, the dimer chain is a prototype of self-organization at surfaces, and its formation process and electronic states have been extensively studied over the past decade for both scientific and technological interests.

On the clean Ge(001) and Si(001) surfaces, the neighboring two surface atoms form a dimer to reduce the number of dangling bonds (DBs) which increase surface energy [12]. The dimer further lowers its energy by tilting (buckling) its dimer bond from the surface plane. These dimers are formed into rows (dimer rows). The buckling orientation of the dimer is alternate in the direction perpendicular to the dimer axis, the dimer-row direction. Similarly to the dimers on the clean surface, the adatoms of group-IV elements on these surfaces form dimers for reducing the number of DBs, and they are often buckled.

Among the group-IV elements on the Ge(001) surfaces, however, little is known about initial growth of Sn. Previous studies on the Sn/Ge(001) surfaces mainly focused on properties of Sn films grown by molecular beam epitaxy, using Auger electron spectroscopy, Rutherford back scattering [13], and atomic force microscopy [14]. The structure of submonolayer Sn atoms, such as whether Sn atoms also form dimer chains or not, has not been reported so far.

In the present paper, we demonstrate by means of scanning tunneling microscopy (STM) that the Sn atoms form two kinds of dimer chains aligning in the ⟨110⟩ and the ⟨310⟩ directions similarly to Si/Si(001) and Ge/Si(001) surfaces [3,4], after Sn deposition onto the Ge(001) surface at RT and 80 K. The ad-dimers in the dimer chain aligning in the ⟨310⟩ direction are intrinsically symmetric (or slightly tilted), whereas those in the dimer chain aligning in the ⟨110⟩ direction asymmetric. At 80 K, the number

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doi:10.1016/j.susc.2007.01.049

density of the dimer chains aligning in the ⟨3 1 0⟩ direction increases while that in the ⟨1 1 0⟩ direction decreases. This suggests that the formation of the dimer chain is governed by the diffusion barrier of the deposited adatom on the substrate as in the model proposed by Qin and Lagally for Si/Si(0 0 1) and Ge/Si(0 0 1) surfaces [3]. We suggest that the diffusion barrier height depends on surface strain, and the existence of the two kinds of dimer chains on the Sn/Ge(0 0 1) surface is interpreted in terms of strain induced by lattice mismatch between adatoms and substrate.

This paper is structured as follows. In the next section, we describe the methods of our experiment. We present the experimental results and discuss them in Section 3. The results for Sn deposition at RT and 80 K are shown in Sections 3.1 and 3.2, respectively. The formation process of the dimer chain is discussed in Section 3.3. Our results are compared with those of the other group-IV elements in Section 3.4. Finally, in Section 4, we summarize these results.

## 2. Experiments

We used two independent STMs for the observation at RT and at 80 K. We acquired all the images in the present paper in a constant-current mode with an electrochemically etched tungsten tip, and analyzed with a homemade program.

The substrate was cut from an *n*-type Ge(0 0 1) wafer (Sb-doped, 0.2–0.4 Ω cm) and rinsed in ethanol and acetone. Then we introduced the substrate into an ultra-high vacuum (UHV) chamber where the base pressure was maintained below $1 \times 10^{-8}$ Pa. A clean Ge(0 0 1) substrate was acquired by repeated cycles of $Ar^+$ sputtering for 20 min at 1 keV and d.c. annealing for 20 min at 920–1000 K in the UHV chamber. Less than 0.1 monolayer (ML) of Sn was deposited onto the clean Ge(0 0 1) substrate at RT and 80 K from an alumina crucible heated with a tantalum filament at a rate of 0.018 ML/min. Here, ML is defined as the number density of Ge atoms at the clean Ge(0 0 1) surface, and $1\ \mathrm{ML} = 6.25 \times 10^{18}/\mathrm{cm}^2$. We monitored the deposition rate with a quartz crystal oscillator, and calibrated it by counting the Sn atoms directly by STM.

## 3. Results and discussion

### 3.1. Sn deposition at room temperature

#### 3.1.1. Sn structures

Fig. 1a shows an empty-state image of the Ge(0 0 1) surface covered with 0.07 ML of Sn deposited at RT. We performed the STM measurement at RT. The arrow in the figure indicates the direction of the Ge dimer rows on the substrate. On the surface, we can see 1D structures extending perpendicularly to the Ge dimer rows. These 1D structures tend to bunch, and inhomogeniously distribute on the substrate. Fig. 1b is a magnified image of the same surface as that in Fig. 1a. The 1D structures consist of three basic components indicated by A, B, and C in the figure.

The positions of the protrusions in these three components with respect to the substrate are illustrated in Fig. 2. The protrusions in the components A and B locate in the trough between the Ge dimer rows. In the component A, they align in the ⟨3 1 0⟩ direction, that is, the separation between the two neighboring protrusions in the dimer-row direction is *a*, the lattice constant of the $(1 \times 1)$ unit cell of the unreconstructed Ge(0 0 1) surface. In the component B, on the other hand, they align perpendicularly to the Ge dimer rows, that is, in the ⟨1 1 0⟩ direction. The component C is a cluster consisting of three

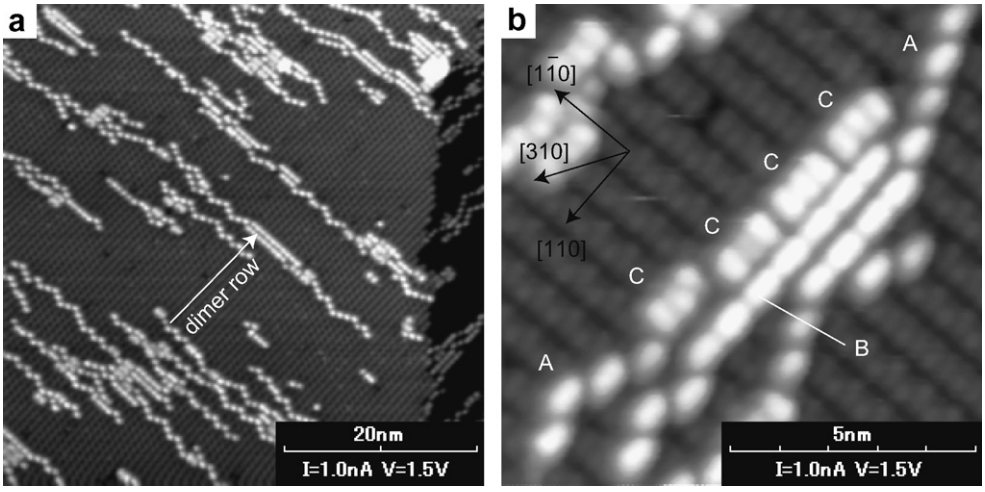


Fig. 1. (a) Empty-state image (tunneling current $I = 1.0$ nA and bias voltage $V = 1.5$ V) of the Ge(0 0 1) surface covered with 0.07 ML of Sn deposited at RT. (b) Magnified image of the same surface in (a). The Sn atoms form one-dimensional structures extending perpendicularly to the Ge dimer row. These surface structures are classified into three components (A, B, and C in (b)). The positions of the protrusions in the three components are schematically illustrated in Fig. 2.