PHYSICAL REVIEW B VOLUME 47, NUMBER 20 15 MAY 1993-II

Ag on the Si(001) surface: Growth of the first monolayer at room temperature

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(Received 21 December 1992)

Growth of the first monolayer (ML) of Ag on the Si(001) surface at room temperature has been studied by means of scanning tunneling miroscopy (STM) and low-energy electron diffraction. Ag atoms form single-layer islands with a density of one Ag atom per Si surface atom. These Ag islands exhibit both local 2×1 and 2×2 order. As the Ag coverage approaches 1 ML, the 2×1 order disappears in favor of the 2×2 order. One ML of Ag is required to complete the first full surface layer. There is no evidence of three-dimensional Ag growth up to 1 ML. Models of the 2×1 and 2×2 surface structures are proposed on the basis of the STM images.

INTRODUCTION

The Ag/Si(001) interface has been studied previously using a variety of surface characterization techniques. Several systematic studies for this system can be found in Refs. 1–3. Scanning tunneling microscopy (STM) has also been used to study this interface.[4–6] STM provides much information on Ag growth behavior on the Si surface and surface structure formation. Overall, these previous STM studies have shown Ag to grow on Si(001) in a Stanski-Krastanov growth mode. However, there is some discrepancy in the structure of the reported grown surfaces.

By using STM and low-energy electron diffraction (LEED), we have studied the initial stages of Ag growth on Si(001) both at room temperature (RT) and at elevated temperatures. We have concentrated here on the growth of the first monolayer (ML) of Ag at RT in order to clarify the results of the previous STM studies in this coverage range. Along with the STM images, models of the corresponding structures are proposed. We also discuss effects of electronic structure on the STM images, and possible implications they have on the measurements. Results of the RT growth behavior above 1 ML and growth at elevated temperatures will appear elsewhere.

EXPERIMENTAL DETAILS

All experiments were performed in an ultrahigh-vacuum chamber having a base pressure of less than 7×10^{-11} Torr. The chamber was equipped with an STM,[7] a four-grid LEED optics, and facilities for sample heating and metal deposition. The Si(001) samples were cut from silicon wafers, chemically cleaned immediately before introduction to the chamber, and then outgassed by heating to 700 °C at a pressure of less than 1×10^{-10} Torr. After outgassing, they were flashed briefly to 1150 °C to remove the surface oxide, cooled rapidly to 1000 °C and held there for 10 min, then cooled slowly to RT. All samples were characterized by both STM and LEED at RT. Ag was evaporated from a tungsten filament onto substrates at RT. The evaporation rate was calibrated versus evaporator filament power by a quartz-crystal thickness monitor, and the Ag coverages were determined from both the power to the evaporator filament and the deposition time. Typical evaporation rates were 0.05 ML/min. One monolayer is defined as the surface atomic density of the Si(001) surface (1 ML$=6.78\times10^{14}$ cm^{-2}). To check the accuracy of the coverage we also count the density of metal-related features on the surface and correlate it with nominal metal coverage in this and other metal on Si systems. Our experience is that our absolute coverages are within 20% of the nominal value, and that relative coverages are considerably more precise.

Since any STM image has a linear distortion that is due to thermal drift during the acquisition of the image, we have applied an appropriate linear mapping to restore the correct aspect ratio and geometry of the structures and thus eliminate the distortion in the image. All of the STM images shown here have been corrected through this process. No other filtering or averaging techniques were used.

RESULTS AND DISCUSSION

Figures 1(a)–1(c) show three STM images of the Si(001) surface with nominally (a) 0.2, (b) 0.5, and (c) 0.8 ML Ag deposited at RT, where (a) and (b) are filled-state images, and (c) is an empty-state image. These three images demonstrate the RT evolution of the surface up to 1

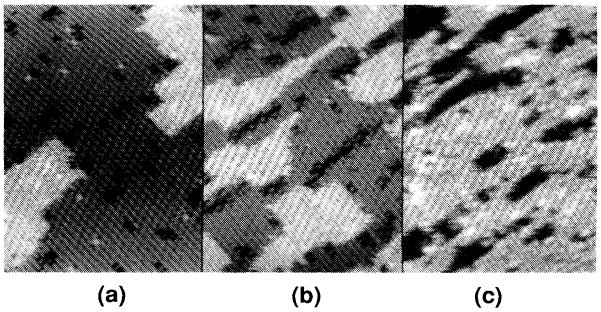

FIG. 1. Three images with (a) 0.2, (b) 0.5, and (c) 0.8 ML Ag deposited at RT. Both filled-state [(a) and (b)] and empty-state (c) images are shown. Single atomic layer Ag islands appear as bright areas at both biases.

ML. In all of these images, the deposited Ag appears as brighter areas on the surface, and rows of substrate Si 2×1 dimers are clearly seen on the areas not covered by Ag.

At the lowest coverage shown in Fig. 1(a), Ag atoms form single-layer islands, about 0.7 Å in height, with edges defined by $\langle 1\bar{1}0\rangle$ directions. As previously reported,[5,6] there is some elongation of the islands in the directions perpendicular to the Si dimer rows, though not to the same extent as in the previous work. Globally, the islands have different sizes and are randomly distributed over the surface. In the areas of uncovered Si between these islands, there are also some small bright features that are due to isolated adsorption of one or two Ag atoms. We will discuss the isolated features in detail shortly.

As the coverage is increased [Fig. 1(b)], we see more of the surface covered in the rectangular single-layer islands. There is a preferential tendency for the islands to grow and coalesce in the direction perpendicular to the Si dimer rows. With further increase in the Ag coverage [Fig. 1(c)], most of the surface is covered in Ag.

There are several aspects of the growth that are apparent in this sequence of images. First, the first layer seems to be largely complete at the highest coverage of 0.8 ML and not at 0.5 ML as has been implied in previous work.[2,4] If we measure the fraction of the surface covered by Ag, we find that for the samples shown in Figs. 1(a)–1(c), 0.21, 0.38, and 0.79 of the surface is covered, respectively. These fractions were evaluated by averaging the results of at least five images of minimum area 500×500 Å^2 at each coverage. The fractional Ag coverage tracks the nominal metal coverage extremely well, further supporting the fact that the first atomic layer of Ag is complete at 1 ML. There is no evidence of three-dimensional (3D) island formation at coverages below 1 ML as reported by Luo, Hembree, and Venables.[2]

There is also a subtle trend seen with coverage in the structure of the Ag within the islands. At low coverage, the Ag in the islands form well-defined rows parallel to the Si dimer row direction, and the maximum for each row is aligned over the trenches between the substrate Si dimer rows. As will be seen at higher resolution, these rows correspond to a 2×1 ordered phase. In Fig. 1(a), there is no obvious corrugation along the length of many of these rows, but there are some areas within each island where there appears to be an additional periodicity along the rows. As the coverage increases, a two unit-cell modulation along the rows becomes more pronounced, and at 0.8 ML [Fig. 1(c)], a distinct 2×2 two-dimensional order is observed in most of the Ag film. This 2×2 ordering has many defects and antiphase boundaries that break up the periodicity for length scales much longer than about 20 Å. This 2×2 phase has been reported in a previous STM study, and here it is clear that it corresponds to 1 ML Ag coverage.[5]

We now examine the small bright features that lie between these islands. Figure 2 shows two areas of the surface with three of these isolated features. These features are the same as those observed by Samsavar *et al.*[4] and can be attributed to adsorption of one or two Ag atoms in bridge sites between Si dimers as shown in Fig. 3. The Ag adsorption also induces buckling of the Si dimers that extends for some distance along the Si dimer rows. A similar effect has been seen for isolated alkali-metal atom adsorption on the Si(001) surface.[8]

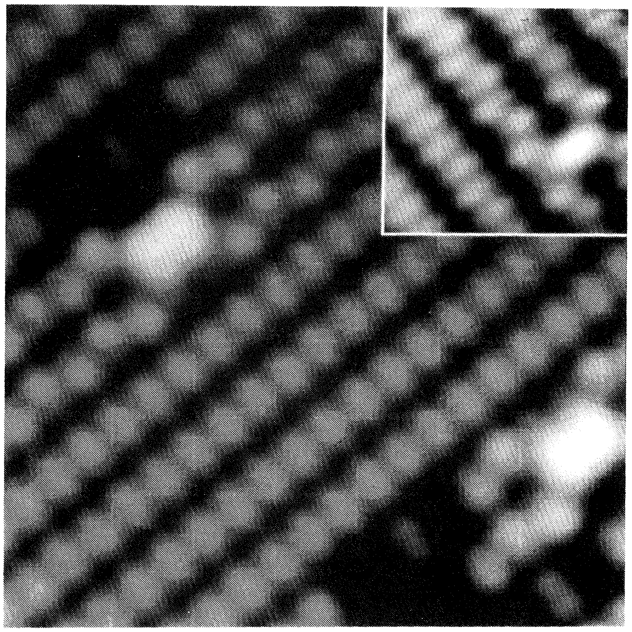

FIG. 2. Isolated adsorption of Ag atoms. The larger image shows two sites, each with two Ag atoms. The inset shows an adsorbed Ag monomer. In both cases, Ag causes buckling of adjacent Si dimers.

The great majority of these isolated features have two Ag atoms, with fewer than 5% being monomers. No longer "chains" of Ag atoms are seen, in contrast with the results of Samsavar *et al.*[4] The question arises as to why some Ag atoms are trapped away from the two-dimensional Ag islands to form these isolated features. The formation of these features appears to be uncorrelated with missing dimer defects in the surface. However, on the clean Si(001) surface, there is a certain density of asymmetric defects, referred to as type-*C* defects by Hamers and Köhler.[9] These defects are absent after Ag adsorption. In addition, the density of the isolated Ag features is about the same as the density of type-*C* defects on the same sample before deposition. It is possible that these defects provide trapping sites for Ag atoms. Type-*C* defects have been shown to be particularly chemically active in oxidation studies.[10] The geometry of the defect, with two Si atoms missing for two unit cells along the dimer row direction, might also make it particularly advantageous for exactly two Ag atoms to adsorb at such a site. Since the type-*C* defects appear to involve missing Si atoms, this raises the possibility that there are missing Si atoms at these isolated Ag features. This is not taken into account in the models shown in Fig. 3.

Figure 4 is a filled-state image showing a two-

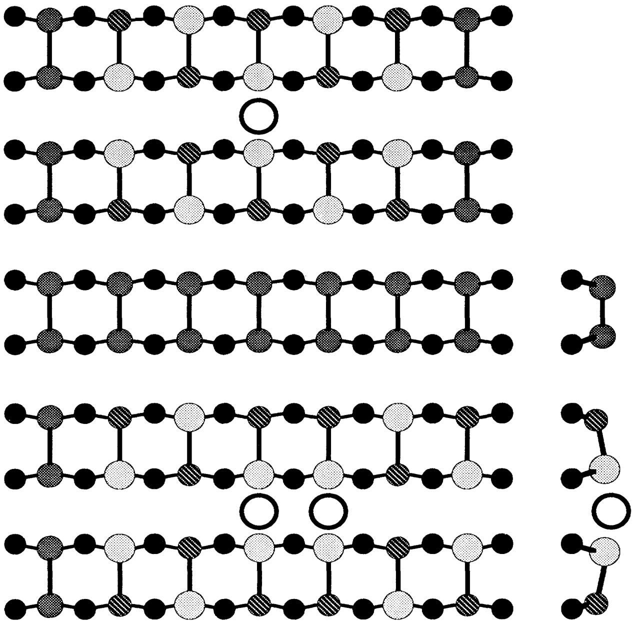

FIG. 3. Structural models for isolated Ag adsorption. Thick white circles represent Ag atoms, while the gray and solid filled circles correspond to Si dimers and the layer of Si atoms just below the dimer layer, respectively. Buckling of Si dimers is shown by a variation in the shading of the dimer atoms. A small inset shows a cross-section view along [110] of both buckled and unbuckled Si dimers.

dimensional Ag island on a surface with 0.2 ML Ag. The dominant structure of Ag in the island is 2×1. There is a two unit-cell ($2a$) periodicity (where $a=a_0/\sqrt{2}=3.84$ Å) in the same direction as the dimerization of the substrate Si 2×1, forming rows with a less well-defined $1a$ periodicity in the perpendicular direction. (Henceforth we denote the Si dimerization direction as $[1\bar{1}0]$ and the dimer row direction as [110]). Along $[1\bar{1}0]$, there is a pair of maxima in each Ag 2×1 unit cell, giving an appearance similar to that of an empty-state image of clean Si(001).

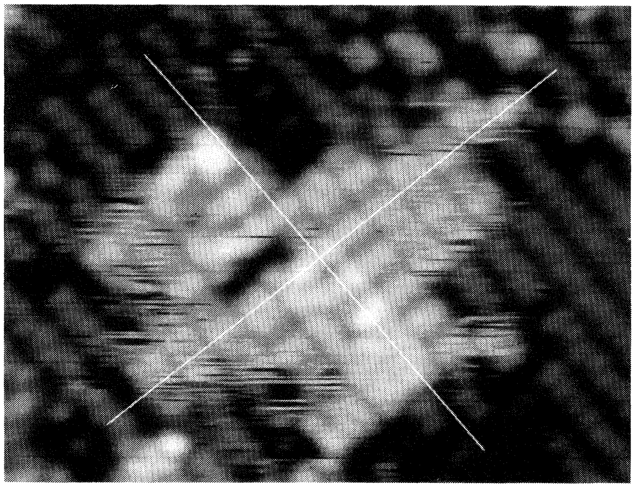

FIG. 4. A filled-state image showing an Ag island on the surface with both local 2×1 and 2×2 structure.

Two lines in $[1\bar{1}0]$ and [110] directions have been drawn on the island extending across to uncovered Si on all sides. The [110] line lies over the position of a trench between Si dimer rows, and the perpendicular line lies between the position of Si dimers. Referring to these lines, it is clear that the Ag 2×1 structure has pairs of maxima situated between Si dimers along the $[1\bar{1}0]$ direction, i.e., the closer spacing between the pairs of maxima is aligned over a Si trench. We will refer to these pairs of Ag maxima as Ag dimers. This pairing of the maxima accounts for the appearance in lower resolution images of Ag rows with a single maximum centered over trench positions, as seen in Fig. 1(a). Since the line along $[1\bar{1}0]$ is aligned with maxima in both the Ag 2×1 and 2×2 structures, this means that the Ag maxima lie between the positions of substrate Si dimers along the [110] direction.

In the region of the island closest to the [110] line, there are areas with $2a$ periodicity along [110] which correspond to the aforementioned 2×2 structure. In this high-resolution filled-state image, the 2×2 phase appears to be the same as the 2×1, except that there is a modulation of the brightness of Ag dimers along each Ag row.

Before we attempt to assign atomic positions to any of the features in Fig. 4, it is important to explore the effects of electronic structure on these images. Figures 5(a) and 5(b) are dual-bias images of a sample with 0.2 ML Ag coverage, taken tunneling into and out of the same area of the surface at sample bias voltages of (a) -1.8 V and (b) 1.8 V, thus reflecting the (a) filled and (b) empty states, respectively. The deposited Ag appears as bright features forming islands at both biases with finer details visible in the filled states. In both images, the dominant features are rows along the [110] direction defining a $2a$ periodicity along $[1\bar{1}0]$. The darker lines between these bright Ag rows are aligned over Si dimer rows of the substrate.

The structure in the empty states is less distinct than the filled states: along the $[1\bar{1}0]$ direction there is only a single maximum per 2×1 unit cell, and along [110] there is no visible corrugation in areas with 2×1 structure. However, in 2×2 areas, the corrugation along [110] is stronger than in the filled states. As a result, the distinction between 2×1 and 2×2 areas is more apparent in the empty-state images.

Figure 5(c) shows the registration of the maxima in the 2×2 phase with respect to the substrate. In the filled states, there are dimerlike structures, centered over Si trenches and spaced $2a$ along [110]. In the empty states, a single maximum per 2×2 unit cell is centered over the same position.

Based on these images, we propose the surface structure shown in Fig. 6. For the 2×1 phase a full monolayer of Ag atoms is placed in bridge sites between the dangling bonds on two Si dimers adjacent along [110], and allowed to dimerize, forming a closer Ag-Ag spacing over the Si trenches. The Si substrate dimerization is assumed to remain intact, as has been suggested in a recent reflection electron microscopy study.[11] This model places an Ag atom in the approximate position of each filled-state maximum in the high-resolution image shown in Fig. 4. The 2×2 phase is assumed to be a weak perturbation of the 2×1 structure where a buckling or some other form of relaxation has concentrated charge density on every second Ag-Ag dimer along the [110] direction. This effect is shown in Fig. 6 by the different size dimers in the 2×2 diagram. The actual nature of the structural difference between the 2×1 and 2×2 phases and its effect on the surface electronic states and the STM images is an open point that will require detailed theoretical modeling.

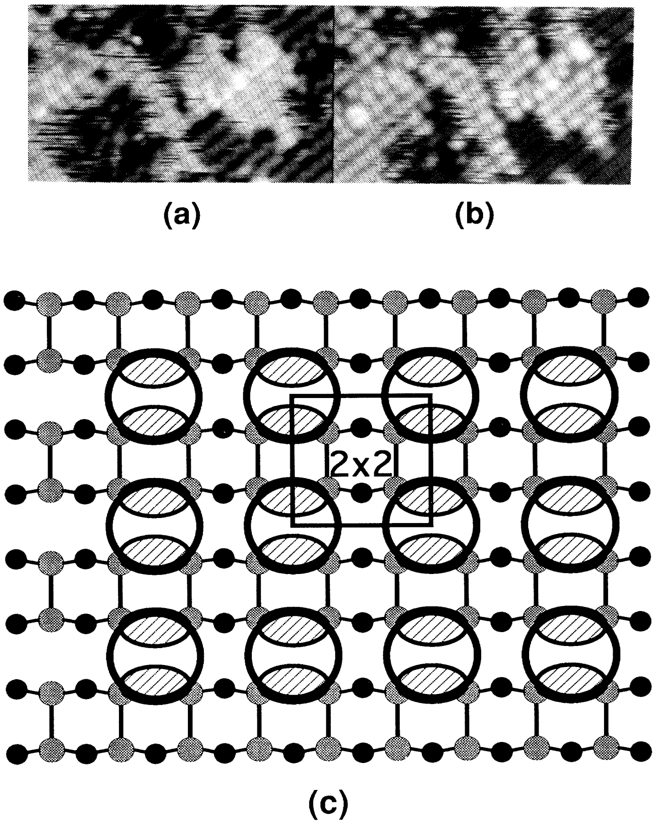

FIG. 5. Dual-bias images of an Ag island showing the (a) filled and (b) empty states of the same area. Panel (c) shows the registration of the maxima in the 2×2 structure with respect to the substrate. The hatched ovals and heavy circles represent the filled- and the empty-state maxima, respectively.

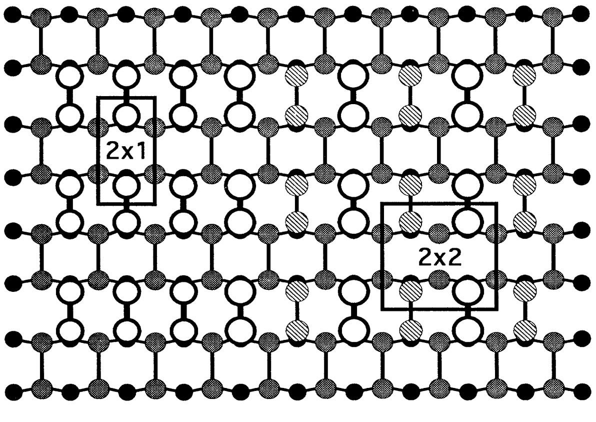

FIG. 6. Surface atomic models for the Ag 2×1 and 2×2 structures. Ag atoms are represented by the circles with heavy outlines. Some Ag atoms in the 2×2 structure are hatched. Dimerized Si atoms in the next two layers are shaded.

As shown in Fig. 1, 2×1 and 2×2 phases coexist during the growth of the first layer of Ag, with the 2×1 phase dominant at low coverages, but gradually supplanted by the 2×2 phase as the coverage approaches 1 ML. The question arises as to why Ag is converted from the 2×1 to the 2×2 structure as the coverage increases. The correlation between the fractional area of the surface coverage by Ag and the nominal Ag coverage illustrated in Fig. 1 implies that the density of Ag is 1 ML in both the 2×1 and 2×2 phases. Thus, 1 ML of Ag can be accommodated in a single layer of either structure, which rules out a simple argument on the basis of crowding. However, we propose that in the 2×1 phase, Ag would ideally like to sit with slightly larger Ag-Ag distances along $[1\bar{1}0]$ than those determined by a strict registry with the underlying substrate. Evidence for this comes from the observation that in the islands at low coverage, the 2×1 structure never has coherent domains of more than about 40 Å (five rows of Ag dimers) along $[1\bar{1}0]$. The 2×1 periodicity is always interrupted by an area of the 2×2 phase. There appears to be no such limit in the length of 2×1 domains in the [110] direction. The finite domain size cannot be due to nucleation of separate 2×1 domains since islands of Ag at low coverages are separated by hundreds of angstroms, and there is no reason that every one of these islands should have several of these nuclei. As the coverage increases and Ag islands coalesce along $[1\bar{1}0]$, Ag has less opportunity to spread out. When Ag is forced to the periodicity of the Si substrate, it forms the 2×2 phase. This picture is consistent with our view that the 2×1 and the 2×2 phases have basically the same structure.

One further point should be made about the nature of the surface at 1 ML which has a direct bearing on our LEED observations during the evolution of the first monolayer. Figure 7 shows 1 ML of Ag in an empty-state image which emphasizes the modulations along Ag rows. This area of the surface also includes a step edge which rotates the Ag row direction. There is a $2a$ periodicity along most of the rows. However, the resulting local 2×2 periodicity does not extend over larger areas, but is split up into many small domains that are coherent over distances of less than 30 Å. However, the $2a$ periodicity perpendicular to the Ag row direction is well defined over larger distances. In our LEED measurements, the initial 2×1 pattern of the clean Si(001) surface changes gradually with Ag deposition in the submonolayer coverage range. Diffuse dots representing 2×1 order remain with increasing deposition up to about 1 ML. No 2×2 dots are seen at any coverage up to 1 ML. The absence of the 2×2 dots can be explained by the small domain

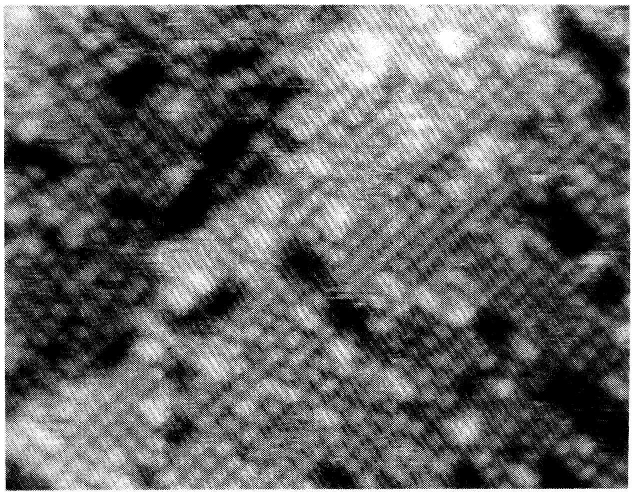

FIG. 7. An empty-state image showing 1 ML Ag deposited on the Si surface, in an area with a single-height atomic step. Ag appears in mainly the 2×2 structure on both the upper and the lower terraces.

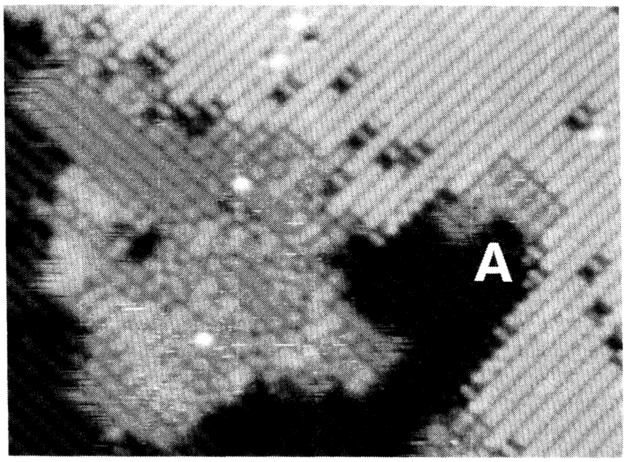

FIG. 8. Ag islands formed at 0.2 ML on the lower edge of a step on the Si substrate. Many different periodicities are seen in the structure of the Ag island. The Ag near label "*A*" is surrounded on three sides by Si atoms in the upper terrace (see the text for details).

size of the 2×2 structure. This domain size was not improved by varying the RT deposition conditions.

The 1-ML surface also shows a small density of bright clumped features, particularly in areas where the 2×2 periodicity is interrupted. These features are also apparent in the coverage evolution shown in Fig. 1, where they are most numerous at the higher coverage. We attribute them to agglomerated Ag that is trapped locally, perhaps by some underlying defect, and is not accommodated into the 2D layer. These clumps cover less than a few percent of the surface, even at 1.0 ML, and each is less than 1.5 Å in height above the surrounding Ag layer. Thus they account for only a small percentage of the total volume of Ag on the surface and their presence does not materially affect our measurements of Ag density. We also distinguish these features from true 3D growth of Ag that occurs above 1 ML. The onset of 3D growth is marked by the formation of much larger islands of metallic Ag.[4]

Figure 8 is a filled-state image which shows an Ag island nucleated on the lower edge of a substrate step edge. This gives us the opportunity to observe the effects that a step edge might have on the ordering of Ag. As is most apparent in the areas closest to the step edge, Ag can exhibit very complicated local structures, with small areas of 2×3 order mixed in with larger areas of 2×1 and 2×2 structure. This is consistent with the qualitative picture that the Ag layer is essentially a 1×1-like structure that has weak interactions with either the underlying substrate and lateral interactions within the layer or with Si at the step edge. On a perfect area of 2×1-ordered Si, Ag forms the 2×1 phase. However, if there is lateral pressure put on the overlayer, other higher-order periodicities are formed. Note, for example, the small area of Ag labeled "*A*" in the figure. This area is enclosed on three sides by Si, and it exhibits a very well-defined $2a$ periodicity along the [110] direction of the lower terrace. This is analogous to our picture of the transition between 2×1 and 2×2 phases as the lateral pressure on the Ag layer increases.

Figure 9 is a large-scale (500×720 Å^2) filled-state image of an area containing two substrate Si domains separated by a step edge. The Ag coverage is 0.2 ML. It is clear that under the RT growth conditions used in this study, there is preferential nucleation of Ag islands on the lower part of the step edge: in the image, virtually all of the step edge has been decorated by Ag covered areas. However, this effect is not strong enough to have a significant effect on the observed density of Ag islands more than several hundred angstroms away from the step edges at low coverages. At higher coverages, the presence of steps has less effect on the areal density of Ag. The average Ag densities cited in the discussion of Fig. 1 include measurements over areas with and without steps.

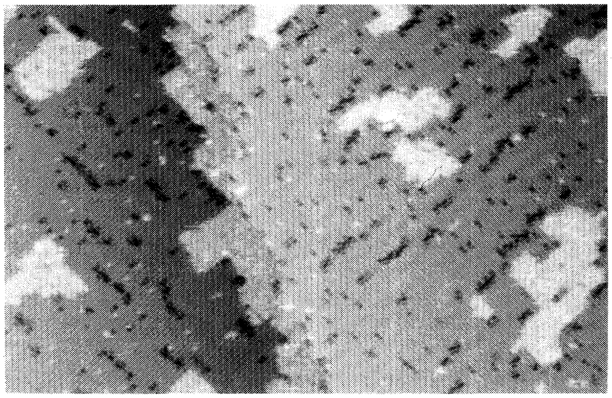

FIG. 9. A 500×720 Å^2 image illustrating preferential growth of Ag at a step edge at 0.2 ML. This image was taken on the same sample as Fig. 8.

No statistically significant effect was seen in these numbers from the presence of steps. Typical step spacings on our substrates were between 300 and 600 Å.

The filled-state image shown in Fig. 10 is specifically taken to illustrate the effect of missing Si dimer defects on Ag growth. This substrate was contaminated with a small amount of Ni, resulting in dark rows of aligned missing Si dimers.[12] A coverage of 0.1 ML Ag was deposited on this surface. As shown in previous STM studies,[4–6] Ag atoms are repelled from missing Si dimer defect sites and do not attempt to fill in these holes. The exclusion of Ag from the Si defects results in a strong elongation of two-dimensional Ag islands in the $[1\bar{1}0]$ direction, similar to the results of Brodde *et al.*[6] As is apparent from the images on cleaner substrates, there is no evidence that Ag growth is preferentially nucleated at missing Si dimer defects. In view of the evident repulsion of Ag from the defects in Fig. 10, it is unlikely that any such defects reside under the areas covered by Ag in images such as those in Figs. 1–9. In fact, at close to 1 ML where the first Ag layer is almost complete (Fig. 7), areas of uncovered Si have a tendency to include such defects: close inspection of such images shows that the holes in the Ag film surround groups of missing Si dimers, and it is, in fact, the shape of these Si defect groups that is often responsible for the elongated shape of the remaining holes in an Ag film such as in Figs. 1(c) and 7.

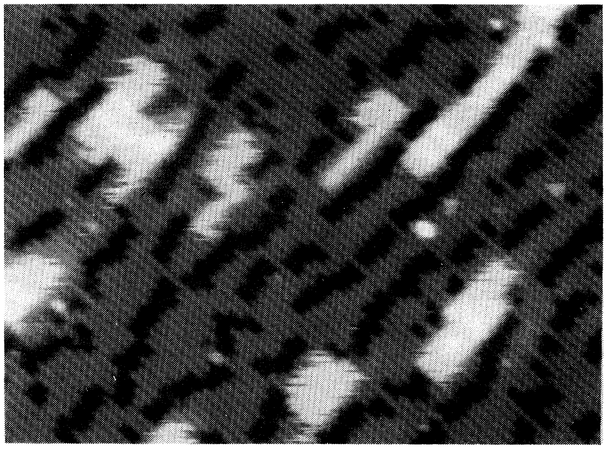

FIG. 10. 0.1 ML Ag deposited on a Si substrate with a relatively high density of missing Si dimer defects, which appear as the black lines running roughly perpendicular to the Si dimer row direction. The Ag atoms (bright areas) are repelled from the Si defect sites.

It should be noted that there is quite a bit of noise in most of these images that appears as horizontal discontinuities aligned with the scanning direction. This effect has been seen in other STM images of this surface[5,6] and is due to the fact that the Ag atoms can move under the action of the tip. This type of noise is seen at both bias voltage polarities, as shown in Figs. 5(a) and 5(b), and at all tunneling currents we have measured (down to 100 pA). The noise is only over Ag islands and is most prevalent around the edges of the islands. This reflects the fact that the Ag near the edges is more mobile than the Ag in the center of the island. At higher coverage, where almost the entire surface is covered by Ag [Fig. 1(c)], there is comparatively little noise. Once Ag is annealed, a different ordered structure is seen, and there is no noise over Ag-covered areas, implying that the surface atoms in the annealed phase are no longer as free to move.[13]

A number of our conclusions differ from those of earlier STM studies and also from a scanning Auger study.[2,4–6] The STM images reported by Hashizume *et al.*[5] are fully consistent with ours, and any difference in interpretation stems from the fact that they show only images at extremely low Ag coverage (0.01 ML). They note the presence of extended rows of Ag running perpendicular to the Si dimer rows. With more Ag on the surface, it is apparent that such rows involve only a small fraction of the total amount of metal. Their suggestion that the 2×2 structure occurs at 0.25 ML is derived from an arbitrary assumption of one Ag atom per unit cell, whereas our assignment of 1.0 ML for this structure is borne out by coverage-dependent measurements. Samsaver *et al.*[4] report the formation of isolated chains of Ag atoms along the Si dimer rows in the low-coverage limit. These chains are very similar to the isolated adsorption features shown in Fig. 2. The fact that they see more of this type of adsorption as opposed to the agglomeration of Ag into islands might have been influenced by the defect density in the original substrates, and also by an Ag evaporation rate that was about ten times higher than in our study. There also might be a slight difference in coverage calibration since they report the growth of metallic Ag islands at >0.5 ML, whereas in our studies we see the growth of similar islands at above 1 ML. Differences with the results of Brodde *et al.*[6] stem from the large missing dimer defect density in their substrates which repel areas of Ag growth, as shown in Fig. 10. There are also differences with the scanning Auger study of Luo *et al.*[2] who report a Stranski-Krastanov growth mode over a range of substrate temperatures, with 3D growth beginning below 1 ML at RT, and an Ag density of 0.5 ML between 3D Ag islands. We have found that the transition from 2D to 3D growth varies with substrate temperature and that our results at elevated temperatures are more similar to the scanning Auger results. In fact, the results from Auger and STM converge for substrate temperatures of about 450 °C. The results for both 3D Ag growth and Ag growth at higher temperatures will be reported elsewhere.[13,14]

CONCLUSIONS

In conclusion, we have provided an atomic view of the growth behavior and the resulting structure and properties of the first atomic layer of Ag on the Si(001) surface at RT. Ag grows as two-dimensional islands with an Ag density of 1 ML within each island. The Ag atoms form rows of dimers residing between Si dimer rows, with either 2×1 or 2×2 two-dimensional periodicities. The first atomic layer is complete at 1 ML Ag coverage and has many small domains of 2×2 order. A structural model is proposed for both ordered phases which places 1 ML of Ag atoms in bridge sites over an underlying Si layer that retains its original dimerization.

ACKNOWLEDGMENTS

This research was partially supported by a grant from the Graduate Research Committee at UW-Milwaukee. We acknowledge the assistance of Jon Glueckstein during some of the experiments.

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[1] G. LeLay, Surf. Sci. **132**, 169 (1983).

[2] Frank C. H. Luo, Gary G. Hembree, and John A. Venables, in *Evolution of Thin Film and Surface Microstructure,* edited by C. V. Thompson, J. Y. Tsao, and D. J. Srolovitz, MRS Symposia Proceedings No. 202 (Materials Research Society, Pittsburgh, 1991).

[3] M. Hanbucken and H. Neddermeyer, Surf. Sci. **114**, 563 (1982).

[4] A. Samsavar, E. S. Hirschorn, F. M. Leibsle, and T.-C. Chiang, Phys. Rev. Lett. **63**, 2830 (1989).

[5] T. Hashizume, R. J. Hamers, J. E. Demuth, K. Markert, and T. Sakurai, J. Vac. Sci. Technol. A **8**, 249 (1990).

[6] A. Brodde, D. Badt, St. Tosch, and H. Neddermeyer, J. Vac. Sci. Technol. A **8**, 251 (1990).

[7] Commercial STM by Omicron Gmbh., Taunusstein, FRG.

[8] T. Hashizume, Y. Hasegawa, I. Sumita, and T. Sakurai, Surf. Sci. **246**, 189 (1991).

[9] R. J. Hamers and U. K. Köhler, J. Vac. Sci. Technol. A **7**, 2854 (1989).

[10] M. Udagawa, Y. Umetani, H. Tanaka, M. Itoh, T. Uchiyama, Y. Watanabe, T. Yokotsuka, and I. Sumita, Ultramicrosc. **42-44**, 946 (1992).

[11] Y. Kimura and K. Takayanagi, Surf. Sci. **276**, 166 (1992).

[12] H. Niehus, U. K. Köhler, M. Copel, and J. E. Demuth, J. Microsc. **152**, 735 (1988).

[13] J. Nogami, X. F. Lin, and K. J. Wan, Bull. Am. Phys. Soc. **37**, 742 (1992).

[14] X. F. Lin, K. J. Wan, and J. Nogami, Phys. Rev. B **47**, 10 947 (1993).

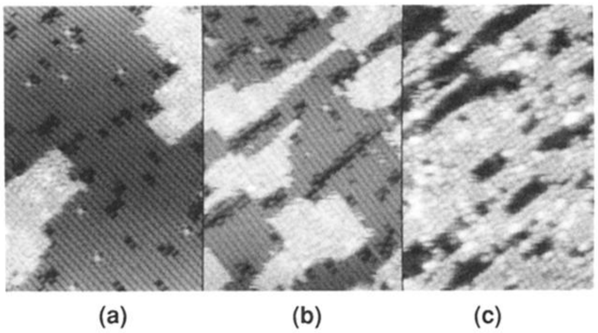

FIG. 1. Three images with (a) 0.2, (b) 0.5, and (c) 0.8 ML Ag deposited at RT. Both filled-state [(a) and (b)] and empty-state (c) images are shown. Single atomic layer Ag islands appear as bright areas at both biases.

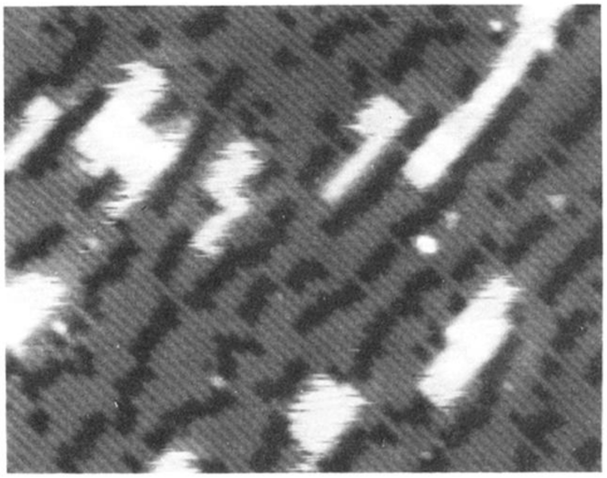

FIG. 10. 0.1 ML Ag deposited on a Si substrate with a relatively high density of missing Si dimer defects, which appear as the black lines running roughly perpendicular to the Si dimer row direction. The Ag atoms (bright areas) are repelled from the Si defect sites.

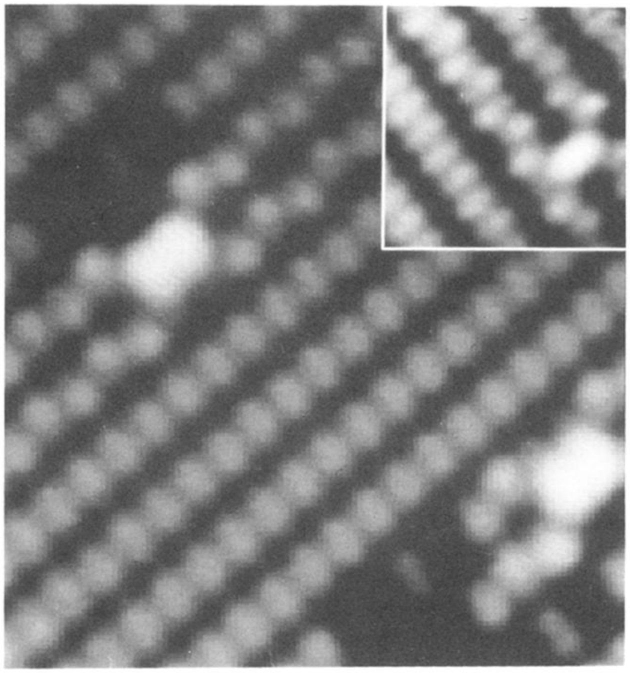

FIG. 2. Isolated adsorption of Ag atoms. The larger image shows two sites, each with two Ag atoms. The inset shows an adsorbed Ag monomer. In both cases, Ag causes buckling of adjacent Si dimers.

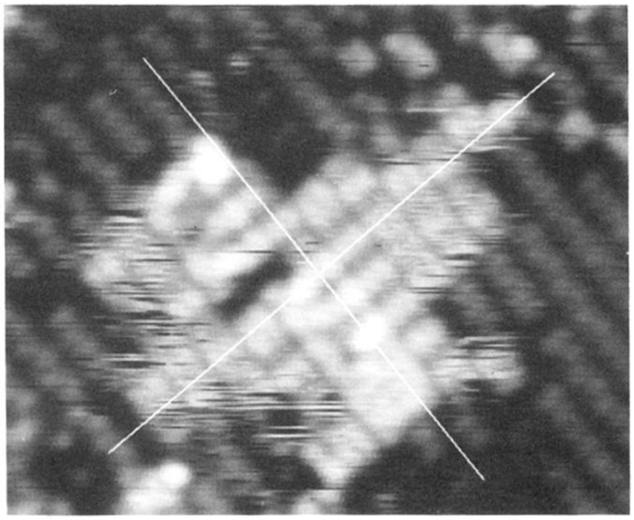

FIG. 4. A filled-state image showing an Ag island on the surface with both local 2×1 and 2×2 structure.

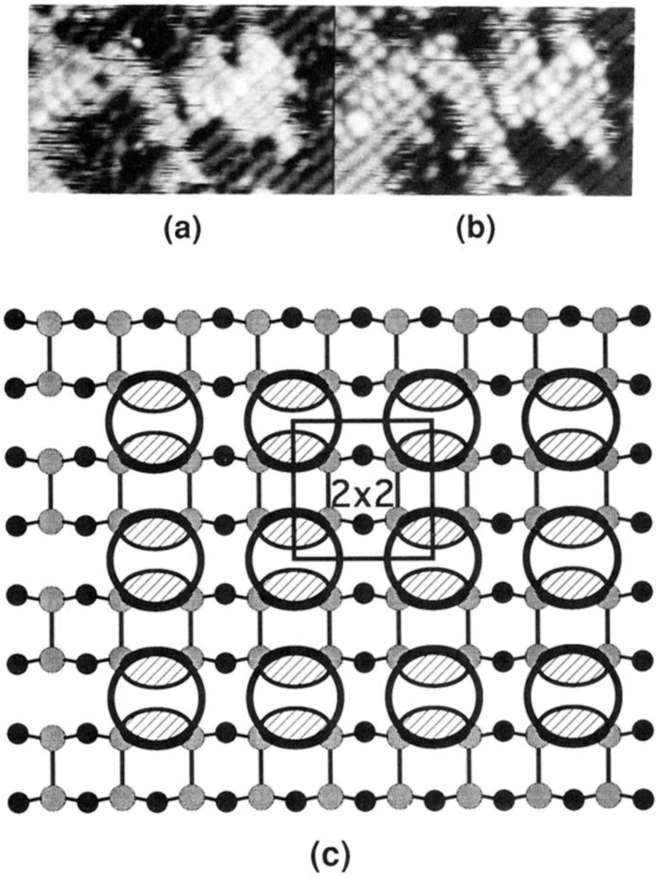

FIG. 5. Dual-bias images of an Ag island showing the (a) filled and (b) empty states of the same area. Panel (c) shows the registration of the maxima in the 2×2 structure with respect to the substrate. The hatched ovals and heavy circles represent the filled- and the empty-state maxima, respectively.

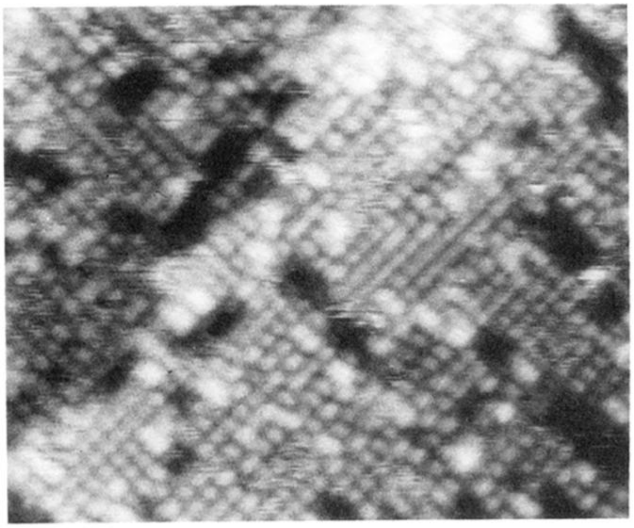

FIG. 7. An empty-state image showing 1 ML Ag deposited on the Si surface, in an area with a single-height atomic step. Ag appears in mainly the 2×2 structure on both the upper and the lower terraces.

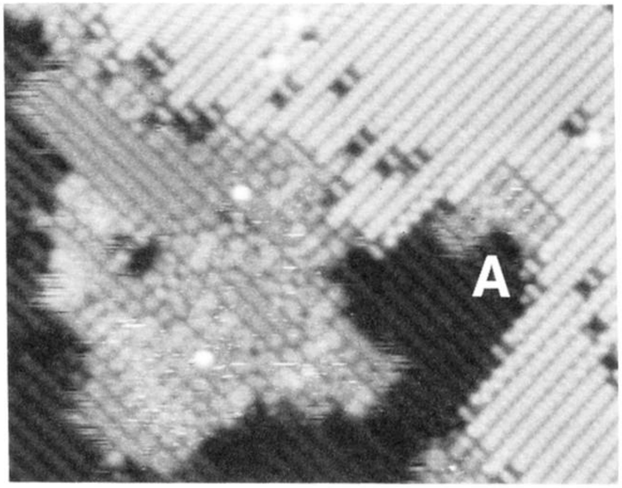

FIG. 8. Ag islands formed at 0.2 ML on the lower edge of a step on the Si substrate. Many different periodicities are seen in the structure of the Ag island. The Ag near label "*A*" is surrounded on three sides by Si atoms in the upper terrace (see the text for details).

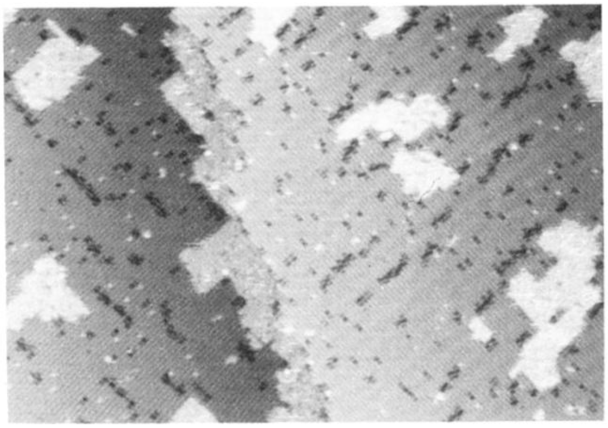

FIG. 9. A 500×720 $\mathrm{\AA}^2$ image illustrating preferential growth of Ag at a step edge at 0.2 ML. This image was taken on the same sample as Fig. 8.