I. INTRODUCTION
The field of epitaxial growth of metal overlayers on metal substrates has been of great interest for many years. The classification of epitaxial growth into three general growth modes has been given in terms of the relative surface free energies of the different metals. For the system of Au on Ag(110), because of the extremely close lattice parameters \(a_{\text{Au}}=4.08\ \text{Å}, a_{\text{Ag}}=4.09\ \text{Å}\), and surface free energies, simple layer-by-layer growth would have been expected. Recently, however, it has been found that a unique growth mode occurs which has been described as "intermixed Stranski-Krastanov" growth,

In this article, we briefly summarize our earlier STM results for Au on Ag(110) at low coverage \(0<2\ \text{ML}\). We present new data for this system suggesting that the 3D islands are indeed thermal equilibrium structures; then we describe samples with higher coverages of Au \(2\ <\ 8<8\ \text{ML}\). The Au continues to grow in an anisotropic fashion along the \([1\ 1\ 0]\) direction of the underlying Ag(110) substrate. Long rows of atoms grow along \([1\ 1\ 0]\) and eventually form the Au \((1\ X\ 3)\) reconstruction. We follow the development of this reconstruction as a function of Au coverage through our STM images.

II. EXPERIMENT
The multichamber ultrahigh vacuum STM apparatus has been described in detail elsewhere. The Ag(110) crystal was cleaned by Ar-ion bombardment \((500\ \text{eV})\) and flash annealed at \(600\ ^\circ\text{C}\). After the sample was allowed to cool for at least 1 h to reach room temperature \((\text{RT})\), it was exposed to Au flux evaporated from a W basket. Au flux was measured using a line-of-sight ionization gauge. For coverages up to 2 ML, most of the evaporations were performed at a constant rate of \(0.6\ \text{ML/min}(1\ \text{ML}=8.45\times10^{14}\ \text{atoms/cm}^2)\), and the gauge was calibrated for Au within 20% by optimizing the sharp \(c(2\times2)\) low energy electron diffraction \((\text{LEED})\) pattern obtained when \(0.5\ \text{ML}\leq\ 0.1\ \text{ML}\) of Au is deposited onto Cu(100). For coverages from 2 to 8 ML, the deposition rate was \(-3.5\ \text{ML/min}\), and the coverage is only accurate to \pm0.5\ \text{ML}. Following sample preparation, no contamination of the surface with O or C was found by Auger spectroscopy.

For coverages up to \(-4\ \text{ML}\), the observed LEED pattern was \((1\times1)\). At \(-5.5\ \text{ML}\), some faint streaks along \((1\times3)\) spot positions appeared. For higher coverage, \((1\times3)\) LEED patterns were observed with some broadening of spots. The STM experiments were usually performed within a few hours after deposition. All STM images were acquired in constant current mode. Low coverage samples \((<2\ \text{ML})\) were mainly measured with negative sample voltage from 30 mV to 2 V, and high coverage samples \((2\ <\ 8<8\ \text{ML})\) were mostly measured with positive sample voltage from 0.1 to 1 V; tunneling currents were generally from 1 to 2 nA. Reversing the sample polarity did not show any spectroscopic effects. Each image was recorded in \approx5-10\ \text{min}. Linear or quadratic background planes have been subtracted from the images, and images were corrected for thermal drift.

III. RESULTS AND DISCUSSION
Au on Ag(110) has previously been studied for coverages from 0.05 to 15 ML by medium energy ion scattering \((\text{MEIS})\) by Fenter and Gustafsson. They interpreted their low coverage blocking curves, however, as evidence for bilayer growth for \(0<0.06\ \text{ML}\). At higher coverage \((4\ <\ 8<7\ \text{ML})\), they report a \((1\times3)\) reconstruction of Au. At even higher coverage \((8\ <\ 15\ \text{ML})\), they finally observed the \((1\times2)\) reconstruction which is characteristic of clean Ag(110). The energetics of fcc(110) missing row reconstructions have been previously calculated for pure metals.

The system has also recently been studied by synchrotron core-level photoemission and reflection high-energy electron diffraction \((\text{RHEED})\) by Hirschorn et al. Although they agree that Au and Ag intercalate for \(\theta<1\ \text{ML}\), they believe that this exchange process continues for multilayer coverages.
The results of our modeling give a best-fit to the blocking  

sion based on the experimental data. This suggests that our  

second layer [see, Figs. 2(a)-2(b)].  

Carlo-type scattering calculations  

a STM image for  

explanation of the MEIS blocking curves, which indicate that  

equilibrium. 6 Subsequent calculations showed that the most  

ceed via subsurface substitution,7 agreeing with our conclu­  

tions of the surface covered by three possible  

figurations: (I) Au on top of the Ag(ll0) surface, (2) a vari­  

able quantity of Au incorporated mainly in the  

growth mode of the system, rather than a kinetically limited  

process.

A. Intermixing growth

The STM images of Au on Ag(110) show no islands and  

no evidence for bilayer steps for \( \theta \leq 1 \) ML. Figure 1(a) shows a STM image for \( \theta = 1 \) ML with single height atomic steps only. If there are no bilayer steps, we must seek another  

explanation of the MEIS blocking curves, which indicate that Au atoms are shadowed even at coverages as low as 0.06 ML.11 A possible explanation is intermixing of the incoming Au with the Ag substrate atoms. We quantitatively reinterpre­ted the MEIS blocking curves by using standard Monte Carlo-type scattering calculations,12 to determine the frac­ tions of the surface covered by three possible Au/Ag con­  

figurations: (1) Au on top of the Ag(110) surface, (2) a vari­  

able quantity of Au incorporated below the top layer of the  

Ag(110) surface, and (3) Au bilayers on top of the Ag(110)  

surface. The details of the calculations are given elsewhere.2 The results of our modeling give a best-fit to the blocking curve data when nearly all of the Au atoms are located below the top Ag layer. For monolayer coverage of Au, the combina­ tion of STM and MEIS data gives a consistent picture, where deposited Au atoms are incorporated mainly in the second layer [see, Figs. 2(a)-2(b)].

Recent first principles total energy calculations showed first, that Au bilayers were unlikely to occur in thermal equilibrium.9 Subsequent calculations showed that the most favorable initial growth process up to 1 ML Au would pro­ ceed via subsurface substitution,2 agreeing with our conclu­ sion based on the experimental data. This suggests that our observations for \( \theta < 1 \) ML are likely to reflect the equilibrium growth mode of the system, rather than a kinetically limited process.

B. Growth of 3D islands

For Au coverage of 1.4 ML, we had previously observed  

2-D finger growth from step edges [Fig. 1(b)], developing  

into widely spaced, anisotropic 3D islands at coverages of  

\( \sim 2-3 \) ML.2 Figures 2(c)-2(d) show a schematic diagram of these stages of growth. The data presented in this article suggest that the extent of this 3D growth is sensitive to temper­

ature and time delay between deposition and measure­

ment. A shortened cooling time of 30 min (versus our cus­

tomary 60 min) after the final anneal may have resulted in a  

substrate warmer than RT, and thus a more fully equilibrated morphology, for some results in Ref. 2. Note that our previ­

ous MEIS modeling suggested that, for \( \theta > 1 \) ML, layers of Au subsequently grow on top of the initial Ag/Au intermixed layer.2

Now we present additional data on the growth of 3D is­

lands for \( \sim 2 \) ML Au on Ag(110). In Fig. 3(a), we show a deposit made at room temperature. Here 2D fingerlike growth from step edges can be seen. Some isolated islands on the finger growth can also be observed. Also apparent are some "holes" as the fingerlike growth does not completely fill in the lower layer before upper layers begin to grow. The same sample is shown on the same scale in Fig. 3(b) in an image obtained after the sample had been left for \(- 3 \) days in the STM ultrahigh vacuum system (base pressure\(< 10^{-10} \) Torr). Anisotropic 3D islands, with typical lengths of 500–

1000 Å, separated by 500–800 Å, are now very evident. The long axis of the islands is along the [110] direction of the  

Ag(110) substrate. Figure 3(c) shows a smaller image on the  

same sample, showing the multilayer, fingerlike end of two islands. Some motion of step edges at the ends of such fin­

gers was observed in subsequent images about 10 min apart;
such step motion has frequently been observed on clean Au(110), though often on a somewhat longer time scale.\textsuperscript{13} These images suggest that the surface evolves with time towards the more stable 3D island structures, although surface contamination after three days is also possible. Figure 3(d), however, shows very similar 3D islands on the same scale as Fig. 3(b) and was obtained from a different sample of 2 ML Au on Ag(110), with Au deposited at room temperature, and then annealed for 10 min at 80 ± 20 °C. This implies that the 3D islands are indeed thermal equilibrium structures, as asserted above, rather than being nucleated by contamination.

C. Development of (1×3) Au reconstruction

At ~4 ML Au coverage, the observed LEED pattern is still (1×1), and the STM images primarily show very flat epitaxial growth (Fig. 4). Anisotropic growth along [110] is still evident, with some isolated atomic-scale rows of the (1×3) structure beginning to be evident as fingerlike growth away from the deposit [Fig. 4(a)]. In addition, careful study of Fig. 4(b) indicates that most atomic rows observed are commensurate with the (1×3) structure of the (110) substrate, with several sets of isolated double rows of atoms on top of the deposit.

At higher Au coverage of ~5.4–8 ML, the (1×3) reconstruction is very evident in the STM images (Fig. 5). Clearly, the atomic rows of the reconstruction grow preferentially along one particular direction, which is the [110] direction of the substrate. From their width, the atomic rows evident in Fig. 5(c) are double rows of atoms. Thus, the (1×3) reconstruction manifests itself as double rows of atoms growing along [110] (see the schematic diagram in Fig. 6); such a model had been previously suggested but not experimentally confirmed.\textsuperscript{4} This structure is a mixture of the (1×2) missing row and (1×1) unit cells, with small (111) facets. Much disorder on an atomic scale is still apparent, with many steps, kinks, and partial rows of atoms [see Fig. 5(c)]. At ~8 ML, additional Au begins to form flatter epitaxial islands [Fig. 5(d)]; presumably, such structures would lead to larger terraces of (1×2) reconstructed Au at even higher coverage.

IV. CONCLUSIONS

The epitaxial growth of Au on Ag(110) is thus a very complicated system, with distinct stages of growth. By combining STM results with reexamination of the MEIS data,\textsuperscript{3,4}...
we have found that Au on Ag(110) at RT grows in an ‘‘intermixed Stranski–Krastanov’’ mode, starting with an Ag/Au intermixed layer followed by growth of 3D Au islands (Fig. 2). As the 3D islands appear to be characteristic of thermal equilibrium structures, the data presented here suggest that the intermixed Stranski–Krastanov growth mode is indeed the thermal equilibrium growth. At higher coverages, we have observed very anisotropic growth along the [110] direction, leading finally to the (1×3) reconstruction of Au for θ=6–8 ML. Some simple simulations of the growth indicate that anisotropic sticking coefficients, with stronger sticking to rows aligned in one direction than to rows in the perpendicular direction, are more important than anisotropic diffusion effects in causing such growth. The anisotropic growth of the Au on Ag(110) for θ>1 ML, first in 2D fingers, then in 3D islands, and finally in the rows of the (1×3) reconstruction, is always along the [110] direction. The growth of Au on Ag(110) appears to be dominated by the effects of the rectangular substrate lattice for all coverages studied here. Far from being the simple system of layer-by-layer growth initially expected, this system has shown many interesting phenomena in its epitaxial growth.

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