

gated via nucleation of dimers at 40 K and subsequent annealing to 110 K and 150 K, respectively. The homogeneous spatial distribution and the narrow range of sizes are obvious in both STM images.

The diffusion barrier of the pre-nucleated dimers is twice as high as that of Ag adatoms¹⁰ and the dimers are stable over an extended temperature range (Fig. 2). On annealing the surface to temperatures >100 K, dimer diffusion and/or dissociation and subsequent adatom diffusion sets in, resulting in the formation of larger clusters by coalescence. The size of these clusters depends exponentially on the annealing temperature.

Diffusion-controlled aggregation can also be used to synthesize one-dimensional aggregates. One-dimensional systems have, indeed, been the focus of much interest because of their unique behaviour and the fact that certain problems can be solved exactly for these systems¹¹. The growth of one-dimensional aggregates makes use of the directional anisotropy of A_{\parallel} (ref. 12). For surfaces with C_{2v} symmetry, there are two different migration barriers, representing two orthogonal directions. An example is the diffusion of Cu atoms on the Pd (110) surface, where the migration barriers are 0.76 and 0.51 eV for the orthogonal [001] and [110] directions, respectively¹³. The value of A_{\parallel} [110] is thus larger than A_{\parallel} [001] giving rise to a faster growth rate along the [110] channels. With decreasing deposition temperature, the ratio of the rate of diffusion along the close-packed direction to that in the perpendicular direction increases. It should therefore be possible to freeze out cross-channel diffusion along [100] while diffusion along the [110] channels is still sufficiently fast. Under such favourable conditions, exclusively one-dimensional chains of adatoms should grow along the [110] direction of the surface.

The experimental realization of such a situation is shown in Fig. 3b, in which Cu aggregates are grown and imaged on the Pd (110) surface at 300 K. At this temperature, the jump rate in the easy [110] direction is 10^4 times higher than that across the channel walls (assuming approximately equal prefactors¹⁴) and we observe the aggregation of long monatomic Cu chains with lengths up to several hundred Å. The average length of these one-dimensional Cu wires can be tailored, for example by varying the deposition temperature. Because diffusion along [100] is already negligible at 300 K, nucleation at temperatures <300 K will also result in the aggregation of one-dimensional chains, the average length of which will decrease with decreasing temperature (that is, decreasing A_{\parallel} [110]). Whereas at 300 K, for a total coverage of 0.05 ML, the monatomic Cu chains consist of an average of 130 Cu atoms, at 180 K (at the same coverage) the average chain is composed of only 10 Cu atoms.

The monatomic Cu chains aggregated on the Pd (110) surface are metastable nanostructures. Upon a short anneal to, or direct growth at, 350 K, two-dimensional lens-shaped islands, several atomic rows wide, are formed. This is demonstrated in Fig. 3c, which shows the structure produced by growth at 350 K: two-dimensional Cu islands with an average aspect ratio of 15 are formed. The metastable character of the long one-dimensional Cu chains is not surprising. Field ion microscopy measurements¹⁵⁻¹⁷ and molecular dynamics calculations¹⁸ have revealed that in general the linear one-dimensional clusters constitute the equilibrium structure only at small sizes ($n < 10$). For Cu on Pd (110), however, recent molecular dynamics simulations¹⁹ reveal that at 0 K one-dimensional chains (which can be very long) are the energetically preferred structures. It appears to be the entropy gain associated with the transition from one to two dimensions that drives the Cu aggregates on Pd (110) to two-dimensional structures at elevated temperatures¹⁹.

This approach of diffusion-controlled aggregation for the synthesis of one- and two-dimensional matter is not restricted to the systems discussed, nor to metal aggregates on metal surfaces. Diffusion-controlled aggregation is applicable for all growth systems in the kinetic regime (including metals on semiconductors or insulators), and one should always be able to find a tempera-

ture window in which one- or two-dimensional aggregates (substrates with directionally anisotropic diffusion) can be produced by manipulating A_{\parallel} and A_{\perp} . □

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Atomic-resolution chemical analysis using a scanning transmission electron microscope

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THE high angle elastic scattering of electrons in scanning transmission electron microscopy depends strongly on the atomic number Z of the sample atoms, through the Z^2 dependence of the Rutherford scattering cross-section¹. The detection of scattered electrons at high angles and over a large angular range (75–150 milliradians) removes the coherent effects of diffraction, and the resulting incoherent image provides a compositional map of the sample with high atomic-number contrast². If a fine electron probe is used, and the sample is a crystalline material oriented along one of its principal axes, individual columns of atoms can be imaged in this way³. Electrons scattered at low angles are not used in this detection scheme, and are thus available for simultaneous electron energy-loss spectroscopy⁴; in principle, this combination of techniques should allow the direct chemical analysis of single atomic columns in crystalline materials. Here we present electron energy-loss spectra from epitaxial interfaces between cobalt silicide and silicon, which confirm that atomic resolution can be achieved by this approach. The ability to correlate structure and chemistry with atomic resolution holds great promise for the detailed study of defects and interfaces.

The basis of obtaining electron energy-loss spectra (EELS) with atomic resolution is the high-resolution Z -contrast imaging technique in the scanning transmission electron microscope (STEM) (Fig. 1). Using the high-angle annular dark-field detector makes thermal diffuse scattering the dominant contribution to the detected intensity and allows us to consider each atom as scattering independently with a cross-section that approaches the Z^2 dependence on atomic number. For thin specimens, where there is no dynamical diffraction, the detected intensity will

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