

construct a device with extremely high confinement properties, that is,  $Q$ -values of up to 45,000. The key to such high  $Q$  lies in the cavity emission pattern: by creating a cavity mode with off-normal emission direction, all the emission is contained in the device by total internal reflection and thereby subject to the full strength of the Bragg reflection of the 2D lattice (Fig. 1). Such an emission pattern can be created by  $k$ -space or Fourier transform engineering of the cavity mode, a method that was first proposed by Painter<sup>3,4</sup>. Despite theoretical proposals<sup>4</sup> predicting  $Q$ -factors greater than  $10^5$ , the best  $Q$ -factors reported in photonic crystal cavities have lagged behind by an order of magnitude<sup>5</sup>, with  $Q \approx 13,000$  being the best reported to date<sup>6</sup>. This discrepancy between theory

and experiment has raised questions about the validity of the models, with possible limitations imposed by material absorption and accuracy of fabrication. The particular merit of the present results has been to demonstrate that Painter's design concepts are valid and can be realised experimentally. Light can be confined to very small spaces indeed, and be persuaded to stay there for a while.

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## SURFACE DIFFUSION

# Shifting strings

Many atomic diffusion processes occur at rates that are too fast to observe experimentally. Using video scanning tunnelling microscopy, researchers are now able to observe the individual steps involved in correlated transport of atomic strings on metal surfaces.

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Understanding atomic transport at surfaces is an old problem, but one that is of ongoing interest as it governs self-organized growth and surface patterning at the nanometre scale. In the past, researchers had to rely mainly on theoretical models to arrive at an understanding of the atomic processes involved in surface reconstructions, phase transformations and crystal growth. Nowadays, techniques such as scanning tunnelling microscopy (STM) and low-energy electron microscopy enable researchers to watch surface transformations as they occur. Such observations reveal that wide regions of a crystal surface, consisting of hundreds of atoms, can appear to move collectively from one image to the next, before coming to rest for long periods of time. But is this motion truly collective, or does it just appear so because the limited observation rate does not allow us to see the atomic diffusion processes occurring in between successive images? Using a home-built video STM with high time resolution, Miguel Labayen and colleagues<sup>1</sup> have revealed the atomic processes underlying the apparent collective motion of long strings of hexagonally arranged Au atoms embedded into the first atomic plane of the cubic Au(100) lattice. Such hex-strings appear in heteroepitaxial metal-on-metal systems; in adsorbed

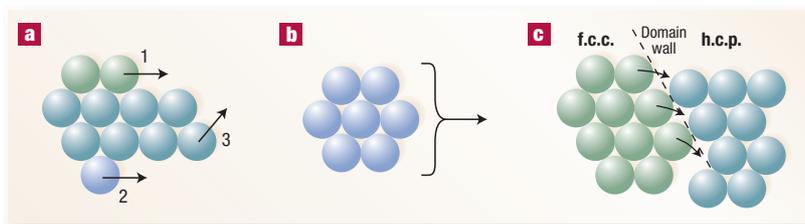
atomic layers; and on the (100) surfaces of Ir, Pt and Au, where they are the precursors of the hexagonal surface reconstructions observed under ultrahigh vacuum<sup>2</sup>.

Diffusion of surface clusters provides a good illustration of the differences between collective, quasi-collective and non-collective diffusion events (Fig. 1). For single-atomic layer Ir<sub>n</sub> clusters on an Ir(111) surface, field-ion microscopy has revealed that the more 'untidy' clusters move by edge diffusion<sup>3</sup>. The low-coordinated edge atoms in these non-compact clusters diffuse in a largely uncorrelated way along the perimeter, constantly changing the cluster shape and centre of mass. This is an example of non-collective diffusion, in which there is no correlation between atomic diffusion events. For the closed-shell clusters such as Ir<sub>7</sub> and Ir<sub>19</sub>, the perimeter atoms are all in high coordination sites and edge diffusion does not occur. Instead, the whole cluster moves by integer lattice-spacings from one observation to the next. This motion is believed to be due to concerted gliding of the cluster<sup>4</sup>. This is a truly collective motion where 7 or 19 strongly bound atoms move at once, interrupted by periods of inactivity. The most intriguing case is quasi-collective motion — a sequence of many single-atom displacements taking place in a correlated manner, and much faster than our observation rate. For clusters, quasi-collective motion has been observed to occur by propagation of domain walls separating f.c.c. and h.c.p. stacking areas in molecular dynamics simulations<sup>5</sup>.

However, despite the important role played by quasi-collective surface mass transport in surface phase transitions, heterogeneous catalysis and crystal growth, the underlying atomic processes at work in real experimental systems are largely unknown.

Labayen and colleagues were able to observe the elementary steps of quasi-collective motion on Au metal surfaces by significantly enhancing the time resolution of the microscopic observation to 10–20 images per second (compared with the 30–200 seconds required to capture a single image in conventional STM). The researchers studied hex-strings 50 atoms long and 5 atoms wide, oriented along the two high-symmetry directions of the square crystal lattice. Two types of string motion were observed: lateral displacements in the direction perpendicular to the string, and, more surprisingly, rapid string motion along the string direction. Motion of the entire string perpendicular to its length was found to be caused by kink propagation along the border between the hexagonally arranged atoms in the string and the surrounding surface, where the atoms form the square lattice of the bulk (100) planes. Kinks are mobile structural distortions that involve local string bending, and were observed to move with a speed of approximately  $0.1 \text{ mm s}^{-1}$ , in agreement with recent observations of rapid dislocation glide at metal surfaces<sup>6</sup>. Kink propagation is also proposed to be a possible origin of the motion along the string direction, which — unlike motion in the perpendicular direction — requires long-range mass transfer from the ‘back’ to the ‘front’ end of the string. The domain wall associated with a kink has a different atomic density from the surrounding region, and can therefore move Au atoms from one string end to the other. Alternatively, the observed motion may be explained by diffusion of an individual atom on top of the string from one end to the other. This idea is supported by *ab initio* density functional calculations showing that the atoms like to stay on the string, where they rapidly diffuse. Unfortunately, these two processes could not be distinguished experimentally.

The observations of Labayen and colleagues make a significant contribution to our understanding of



**Figure 1** Non-collective, collective and quasi-collective atomic diffusion processes. **a**, Uncorrelated diffusion of edge atoms results in non-collective transport of atomic clusters. **b**, Truly collective motion of atomic clusters, where the whole cluster moves as one unit. **c**, Quasi-collective motion occurs when many single-atom displacements occur faster than we can observe them — as in the propagation of domain walls between f.c.c. and h.c.p. areas, for example.

quasi-collective motion at surfaces. Nonetheless, the biggest mystery inherent in quasi-collective motion — the extended periods of inactivity — remains unexplained. That the many individual atomic processes all take place in a very short time means that displacement of a single atom must induce a whole chain of atomic displacements, which all become more probable once the first atom has moved — much like a chain of dominoes. In other words, the individual events have to be statistically correlated. Although the required correlation appears natural for kink motion along a chain, it is less intuitive for atoms exiting the surface at one string end and diffusing on top of the hex-string to its other end. This motion along the string direction may not be quasi-collective, as displacement of the string by one atomic length would require only a single atom to move. Although the mechanisms giving rise to the correlations between individual atomic events remain to be discovered, Labayen and colleagues have dramatically illustrated how the development of experimental techniques, the use of theory, and the appropriate choice of model systems give us a unique insight into the complex dynamic behaviour associated with mass transport at surfaces.

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