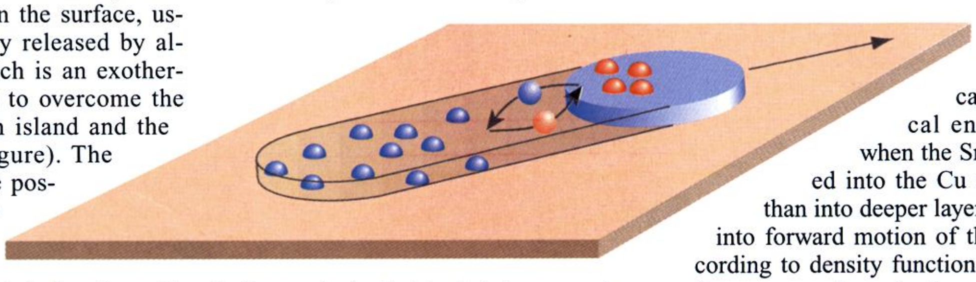
PERSPECTIVES: SURFACE SCIENCE

How to Power a Nanomotor

Flemming Besenbacher and Jens K. Nørskov

Nanomotors are a particularly attractive goal for nanotechnology. Such nanometer-scale structures capable of converting chemical energy into work will be needed in many types of nanodevices, including switches, pumps, and actuators. To construct a nanomotor, we need to find ways of making nanostructures propel themselves and experimental methods that can track the motion.

The work of Schmid *et al.* on page 1561 of this issue can be viewed as a direct observation of a nanomotor (*1*). The authors find that nanoscale islands of tin deposited on a copper surface spontaneously move around on the surface, using the chemical energy released by alloying Sn into Cu (which is an exothermic chemical reaction) to overcome the friction between the Sn island and the Cu surface (see the figure). The observations were made possible by applying two complementary experimental techniques, the scanning tunneling microscope (STM) (*2*) and the low-energy electron microscope (LEEM) (*3*), to obtain information about the atomic-scale structure as well as the motion of the islands on the surface.



Let alloy formation do the work. An Sn island skates around on a Cu(111) surface while exchanging Sn atoms for Cu atoms.

The development of the STM (*2*), in which a tip is raster-scanned across a surface and a small tunnel current (on the order of a nanoampere) is recorded in each pixel, has revolutionized the field of surface science, because it allows the structure of surfaces to be explored with unprecedented resolution. Direct real-space images of individual atoms and molecules on surfaces can now be obtained on a routine basis. Another very successful new microscope, the LEEM (*3*), exploits the wave nature of electrons that are scattered elastically from a surface. With this microscope, entities on the surface that are larger than 5 to 10 nanometers can be imaged and followed over time. The LEEM differs from conventional electron microscopes in that the electrons are of much lower energy (1 to 100 eV), enabling the LEEM to only observe surface features; the image contrast is based on diffraction of the electrons. The LEEM superbly supplements the STM, and in combination, the two techniques bridge the gap between mesoscopic and atomic-scale structures on surfaces.

Alloying in the first layer of a metal surface is vastly different from alloying in the bulk. In fact, a new type of two-dimensional alloy phase that only exists in the outermost surface layer has recently been discovered (*4*). Density functional calculations have provided a thorough database of phase diagrams that can be used to predict the existence of surface alloys (*5*). Metals that do not alloy in the bulk may alloy at the surface, and even for stable bulk alloys, there can be large differences in the stability of the bulk and the surface alloy. These new surface alloy phases open up new possibilities for designing materials with interesting physical and chemical properties (*6*).

The effect studied by Schmid *et al.* exemplifies some of the special properties of surface alloys. Just after deposition of Sn on a Cu(111) surface [where (111) denotes the exposure of the densest possible surface of the bulk material], the Sn atoms coalesce into large islands containing ~100,000 atoms. The alloying of Sn with Cu is an exothermic process, leading to the formation of a bronze (*7*), but the process is even more exothermic if Sn is in the topmost layer. Exchange between an Sn atom in the island and a Cu atom in the layer just underneath the island is therefore possible. It is more energetically favorable, however, if the island moves away from the location at which the exchange takes place. The island cannot move in a direction where exchange has already happened because it is repelled by the mixed phase, and therefore the Sn islands are constantly seeking out new areas on the surface that do not yet contain any Sn.

Only the combined use of the two powerful experimental techniques allowed Schmid *et al.* to study the needle in detail (the formation of the bronze alloy on the nanoscale) with the STM while at the same time keeping an eye on the haystack (the correlated motion of the Sn islands on the Cu surface on a mesoscopic scale) with LEEM. The experiments show in unprecedented detail how even a relatively simple system consisting of one metal deposited on another can exhibit very complex dynamics. One may envision using this nonrandom process as a mechanism for organizing nanoscale alloy structures over large length scales.

The system studied by Schmid *et al.* can be considered as a paradigm for a new class of nanomotors in which chemical energy is converted into work. In this case, the chemical energy released when the Sn is incorporated into the Cu surface (rather than into deeper layers) is converted into forward motion of the islands. According to density functional calculations, the energy released when an Sn atom is segregated from the second layer (below the Cu-Sn island) to the surface of Cu(111) is on the order of 1 eV (*7*). From the experiments, the Sn-Cu exchange rate is about one atom per 4000 s at room temperature. An island with 100,000 atoms will therefore release on the order $1 \times 100{,}000/4000$ eV/s $\cong 25$ eV/s $\cong 0.5 \times 10^{-20}$ horsepower (hp). This implies that the power-to-weight ratio is roughly 0.3 hp/kg. For comparison, a car typically has 100 hp and a weight of 1000 kg, giving a similar power-to-weight ratio of 0.1 hp/kg.

The challenge is to devise nanomotors whose motion can be controlled externally (so that they can be used to move things around at will) and that can be refueled. These two requirements may be coupled if the availability of fuel can be controlled externally. The principle behind the Sn/Cu motor may be extended to the incorporation of molecules supplied from the gas phase through islands into a more stable compound in the surface.

References

1. A. K. Schmid, N. C. Bartelt, R. Q. Hwang, *Science* **290**, 1561 (2000).
2. G. Binnig, H. Rohrer, *Rev. Mod. Phys.* **59**, 615 (1987).
3. E. Bauer, *Surf. Sci.* **299/300**, 102 (1994).
4. L. Pleth Nielsen *et al.*, *Phys. Rev. Lett.* **71**, 754 (1993).
5. A. Christensen *et al.*, *Phys. Rev. B* **56**, 5822 (1997).
6. F. Besenbacher *et al.*, *Science* **279**, 1913 (1998).
7. A. Ruban, private communication.

F. Besenbacher is at the Institute of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark. E-mail: fbe@ifa.au.dk J. K. Nørskov is in the Department of Physics, Technical University of Denmark, DK-2800 Lyngby, Denmark. E-mail: norskov@fysik.dtu.dk Both are associated with the Center for Atomic-Scale Materials Physics.