SCANNING PROBES

Cold-atom microscope shapes up

The ultrasoft 'tip' of the cold-atom scanning probe microscope will offer new possibilities for exploring the interactions between atoms and surfaces.

Christian L. Degen and Jonathan P. Home

Gases of ultracold atoms have allowed a variety of new physical phenomena to be studied since the first Bose–Einstein condensate — a type of matter in which all the atoms occupy the same quantum ground state — was produced in 1995. In those early experiments, laser cooling was used to reach microkelvin temperatures, and magnetic traps were then used to store the atoms and move them around. The magnetic fields in these traps were generated by passing current through macroscopic coils, but nowadays many researchers use much smaller 'atom chip' traps in which the magnetic fields are generated by micrometre-scale electronic circuits that have been fabricated by lithographic techniques. Atom chip traps offer stronger trapping potentials and more flexibility in experimental design than do traps of the previous generation, and they are routinely used to produce ultracold gases containing only a few thousand atoms and to position these gases reliably in three dimensions with a precision of a few nanometres. Writing in *Nature Nanotechnology*, Andreas Günther, József Fortágh and co-workers at the University of Tübingen now report that a gas of ultracold atoms in an atom chip trap can be used as an ultrasensitive probe to image and investigate surfaces with microscopic resolution[1].

A potential concern with atom chip traps is the proximity of the ultracold gas, which is very delicate, to the surface of the chip, which remains at room temperature and is only a few tens of micrometres away. Atoms in the gas can directly collide with the surface, and electric and magnetic noise from the surface can excite the atoms into higher energy levels. Both of these mechanisms will eventually lead to the loss of atoms from the gas. However, these mechanisms can also be used to study the physical nature of the underlying interactions between the atoms and the surface, and, ultimately, to learn something new about the properties of the surface.

The Tübingen team has now demonstrated how the various interactions can be turned into useful imaging modalities for high-resolution microcopy[1]. In one experiment, they found that the loss rate of the cloud — in their case, a Bose–Einstein condensate containing about 20,000 rubidium-87 atoms — was a reliable measure of surface proximity, and went on to show that a single, free-standing carbon nanotube could be imaged with a precision of roughly ±0.3 μm. In a second experiment, they demonstrated that equally well-resolved images could be produced by measuring how proximity to the surface changed the amplitude and frequency at which the condensate oscillated within the trap. Monitoring these oscillations allows the curvature and anharmonicity of the trapping potential to be determined directly, from which local information about electrostatic and dispersive forces can be deduced. This second approach does not involve a significant loss of atoms from the gas. In the experiments, the temperature of the gas was less than 1 μK and the sample was at room temperature.

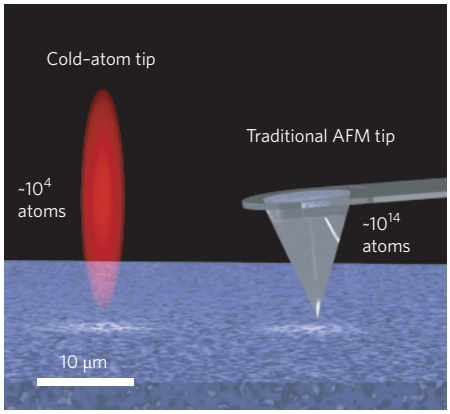

Figure 1 | Cold-atom microscope and conventional AFM in comparison. Artist's impression (to scale) of the solid tip in a conventional AFM (right) and the trapped gas of ultracold atoms (left) that is used at the tip in the cold-atom scanning probe microscope developed by Günther, Fortágh and co-workers[1]. The cold-atom probe tip is similar in size to the AFM tip, but is roughly 10^{15} times softer (that is, lower in effective spring constant), allowing it to measure surface–tip interactions over larger distances than is possible with a conventional AFM. However, the apex of the AFM tip is much sharper, which leads to higher spatial resolution. The cold-atom probe tip contains approximately 20,000 rubidium-87 atoms, whereas the AFM tip contains roughly 10^{14} atoms.

The operating principles of the device built by Günther, Fortágh and co-workers[1] are directly analogous to those of the atomic force microscope (AFM; Fig. 1). In a conventional AFM, a cantilever with an extremely sharp tip is scanned over a surface, and interactions between the surface and the tip cause the cantilever to move up or down or make the oscillation frequency of the cantilever change. Measuring these changes as the tip is scanned allows an image of the surface to be built up. In the cold-atom scanning probe microscope developed by the Tübingen team, the ultracold gas plays the role of the tip (Fig. 1).

It is instructive to compare the mechanical properties of a cold-atom probe with those of AFM cantilevers. Conventional silicon microbeams, for example, have spring constants of typically 1 N m^{-1}. This high stiffness allows the AFM to be operated within a few nanometres of the surface of interest, but limits the force sensitivity. The ultracold gas used by the Tübingen team[1], on the other hand, behaves like a cantilever with a spring constant of 10^{-15} N m^{-1}. (The nominal spring constant of the ultracold gas is $k = m\omega^2$, where m is the total mass of the atoms in the trap and ω is the trap frequency.) This is about fifteen orders of magnitude softer than conventional AFM cantilevers and about nine orders of magnitude softer than the softest solid mechanical oscillators in routine use[2] (devices based on semiconductor nanowires and carbon nanotubes). This ultrasoft behaviour renders the cold-atom probes so sensitive that relevant data, such as Casimir–Polder forces, can still be detected several micrometres from a surface[3]. Cantilever-based force sensors, however, perform best at tip–sample separations of less than 10–100 nm. Thus, the cold-atom scanning

probe microscope could greatly extend the distance range over which the weakest surface forces can be measured.

The spatial resolution of cold-atom probes is still several orders of magnitude lower than the atomic-scale resolution that is achieved using AFMs. The Bose–Einstein condensate tips, for example, had dimensions of about 5–20 μm, which limits the imaging resolution and closest operating distance to several micrometres. As the tip size is primarily set by the number of atoms in the cloud and the strength of the confinement potential, reducing the atom count and using even smaller (and stronger) traps will possibly lead to submicrometre spatial resolution. Indeed, if a single atom could be held in a 1-MHz trap, the tip size would be reduced to a mere 10 nm (ref. 1).

Probes made of ultracold atoms or molecules could also become a fruitful arena for the investigation of chemistry at the gas–solid interface. For example, by bringing trapped molecules towards a carefully prepared surface in a controlled way, it should be possible to study the chemical reactions between the molecules and the surface. Indeed, intriguing experiments have recently been performed with ions, atoms and molecules in the gas phase, and have shown striking quantum behaviour[4–6]. Extending this 'cold chemistry' to solid surfaces would enable the study of catalytic reactions and processes such as adsorption and desorption in the ultracold regime. Another possibility would be to use cold-atom probe tips to chemically modify surfaces with high spatial resolution. The work at Tübingen[1] provides an exciting example of how quantum physics can be turned into an important new tool for nanoscale science and technology. ❐

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CONDENSED MATTER PHYSICS

Superconductivity at the double

Electrostatic doping of the transparent insulator potassium tantalate with an electric double-layer transistor has allowed superconductivity to be observed in this material for the first time.

Kosmas Prassides

Superconductivity has been at the forefront of condensed-matter research ever since Heike Kamerlingh Onnes discovered 100 years ago that mercury completely loses its resistance to electric currents when cooled below a critical temperature. The discovery of new superconductors — which are also able to expel magnetic fields — has traditionally depended on the chemical manipulation or doping of parent materials to increase the concentration of charge carriers, or on the use of external pressure to control their lattice and electronic structures. Writing in *Nature Nanotechnology*, Masashi Kawasaki, Yoshihiro Iwasa and co-workers[1] at Tohoku University and the University of Tokyo report a powerful experimental tool for discovering new superconductors in families of materials where conventional chemical routes have failed to do so before.

The approach relies on electric fields to increase the concentration of charge carriers — a process known as electrostatic doping. Using a hybrid device called an electric double-layer (EDL) transistor, which can sustain very high electric fields and high charge densities at surfaces, Kawasaki, Iwasa and co-workers succeeded in driving potassium tantalate ($KTaO_3$), which is an insulator with a wide bandgap, into a superconducting state. The critical temperature was 50 mK.

The concept of the EDL was first introduced in the nineteenth century and it refers to the array of charges that exist at the interface between an electronically conducting solid and an ionically conducting electrolyte[2]. In general, the EDL consists of a layer of electrons at the surface of the solid and a layer of ions adsorbed on the surface, with the two layers being separated by less than a nanometre. The solid/electrolyte interface therefore behaves like a nanogapped capacitor with a very large capacitance. Moreover, this capacitor forms in a self-organized manner when a potential difference is applied across the solid and the electrolyte.

To make an EDL transistor, the gate dielectric in a conventional field-effect transistor (FET) — the solid layer of insulating material that separates the semiconducting channel from the metal gate electrode — is replaced by an ionically conducting electrolyte[3]. When a positive (or negative) voltage is applied to the gate electrode, mobile anions (or cations) in the electrolyte are attracted to the electrode by the positive (or negative) surface charge, and an EDL forms at the interface between the electrode and the electrolyte. A second EDL is established at the interface between the semiconductor and the electrolyte as an equivalent density of cations (or anions) accumulates and induces a negative (or positive) surface charge (Fig. 1).

The consequences of this change turn out to be profound. In a conventional FET device, the gate dielectric (which is typically SiO_2 or Al_2O_3) breaks down owing to charge recombination when the electric field exceeds ~1 MV cm^{-1}, and this limits the charge carrier density at the surface to ~10^{13} cm^{-2} or less[4]. EDL transistors, on the other hand, are more resistant to dielectric breakdown because of their intrinsic self-healing characteristics. The recombination of electrons from the semiconductor surface with positive ions in the electrolyte leads to the formation of neutral electrolyte molecules, which are simply replaced by new positive ions that are attracted to the interface by Coulomb forces. EDL transistors can sustain electric fields of ~10 MV cm^{-1} or higher, which allows the charge carrier density at the surface of the semiconductor channel to be increased to very high values as the applied gate voltage increases.

Further optimization of the EDL transistor performance has been achieved by changing the nature of the electrolyte: whereas polymer/ionic salt electrolytes such as polyethylene oxide/$KClO_4$ can sustain