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Imaging techniques

A record-breaking microscope

Microscope paves the way for the ultimate imaging technique

An electron microscope has been developed that produces images at higher resolution than conventional approaches, and which is suitable for studying fragile materials that can be damaged by electron beams. See Article[1]

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On page XXX, Jiang *et al*[1]. report the highest-magnification image ever obtained using a transmission electron microscope. The image reveals the atoms in a two-dimensional, self-supporting sheet of a semiconductor, and has a resolution is 0.39 ångströms; for comparison, most atoms are about 2–4 Å in diameter. The work should eventually provide new insight into the burgeoning field of two-dimensional materials, examining them with unprecedented precision. It may also lead to a method of imaging individual atoms in 3D objects.

To generate the image, the authors used a method called ptychography (the ‘p’ is silent) in which electrons are passed through a specimen to produce many 2D electron-diffraction patterns. The basic principle of the technique was proposed almost 50 years ago by the physicist Walter Hoppe, who reasoned that there should be enough information in this type of diffraction data to work backwards to produce an image of the diffracting object[2]. However, it was many years before computer algorithms were developed that could do this reverse calculation easily and reliably[3,4]. The pictures produced by ptychography are therefore generated using a computer from a vast amount of indirect scattering data. An important advantage of the approach over conventional microscopy techniques is that it can surpass the resolution limit imposed by lens-imaging theory. In fact, it can work without any lenses at all[5].

Over the past 10 years, ptychography has been widely used for microscopy in the X-ray[4], extreme ultraviolet[6] and visible-light[7,8] regions of the electromagnetic spectrum. It has also been somewhat successful when used with electrons, but Jiang and colleagues are the first to show that it can surpass the resolution of microscopy that uses the best electron lenses. The problem has been that the scattering patterns needed for electron ptychography contain both extremely bright areas and very dark regions, i.e. they have high dynamic range. For the technique to work, every single electron must be counted near-perfectly. Worse, a thousand diffraction patterns must be recorded every second. Speed, accuracy and dynamic range are conflicting performance parameters in any electron detector. All previous work has compromised on one or more of these properties. The authors' key achievement is to implement a new detector that can handle such demanding specifications.

Remarkably, Jiang *et al*. gave themselves a huge handicap as far as beating the resolution record is concerned. For any given microscope lens, the best resolution is achieved using the shortest wavelength of the radiation or electron beams concerned. However, the authors used relatively low-energy electrons, which have twice the wavelength of those that are used in the very highest resolution lens-based microscopes[9,10]. Using low-energy electrons for microscopy is good, because it greatly reduces the damage inflicted on the specimen by the electrons. But in this case, it also meant that the resolution of the lens had to be improved by more than a factor of two just to match, let alone beat, the resolution record.

But achieving high resolution is not the whole story. Anyone with poor eyesight knows that they need as much light as possible if they want to read small print. This is because there is an intimate relationship between resolution, contrast (the difference between the darkest and lightest parts of an object) and flux (the amount of light illuminating the object). If the small print is light grey, not black, then the contrast is low, and even more light is needed to read it.

The same is true for an electron microscope. Jiang and colleagues use ptychography to recover the phase change that the electron wave has acquired in passing through the object, which is a very strong source of contrast, even for low atomic-number atoms. Consequently they need relatively few electrons to make their images compared with other state-of-the-art techniques (such as the ADF image shown in Figure 1a below). So not only did Jiang and colleagues use low-energy electrons without compromising resolution, they also needed far fewer electrons, thus further reducing the damage done to the sample.

Perhaps the most striking feature of Jiang and co-workers’ image is not the atoms themselves, but the enormous gaps between them. Average bond lengths in a material can be measured in a bulk sample by all sorts of diffraction and spectroscopic methods, but these images give a very precise experimental measure of the bond lengths between individual pairs of atoms, which are sensitive to their specific local bonding environment. But are ultra-high resolution gaps useful for anything else?

I think the answer lies in the big success story of X-ray ptychography: tomography [4], a technique in which lots of 2D images of a transparent object are acquired as it is rotated, so that a 3D image can be built up. Phase information is an ideal imaging signal for this technique. But when images are taken through a solid object, the resolution needs to be as high as possible to distinguish features lying on the top surface from those at the bottom, many of which will seem (when seen in projection) to be laterally close to one another. Jiang *et al*. demonstrate that their electron microscope might well be capable of being used for tomography: indeed, they test the resolution of it by putting two layers of atoms on top of one another, and measuring the minimum apparent lateral distance between atoms in different layers, some of which were almost overlapping each other. In theory, this multiple layering is not limited to 2D materials, but could be used to image any complicated non-crystalline, amorphous of non-equilibrium material. Unfortunately, for yet thicker objects the electron waves scatter so strongly that they spread out and re-interfere in complicated ways so that the underlying structure is even harder – though in theory, possible – to work out.

Perhaps the take-home message of this work is not so much the record resolution, or its applications to 2D materials, but the fact that it opens up the possibility of an ultimate imaging instrument: a microscope that could image the 3D bonding of every individual atom in a solid volume of matter, while at the same time using a minimal flux of damaging electrons. Indeed, the authors allude to this enticing possibility in their conclusions, suggesting perhaps that tomography is what they themselves are planning to do next with their remarkable detector. The prize would be in solving the exact 3D atomic structure of the wide class of non-periodic solid-state structures, such as glass and amorphous metals, for which we currently must infer candidate structures from averaged bulk measurements.

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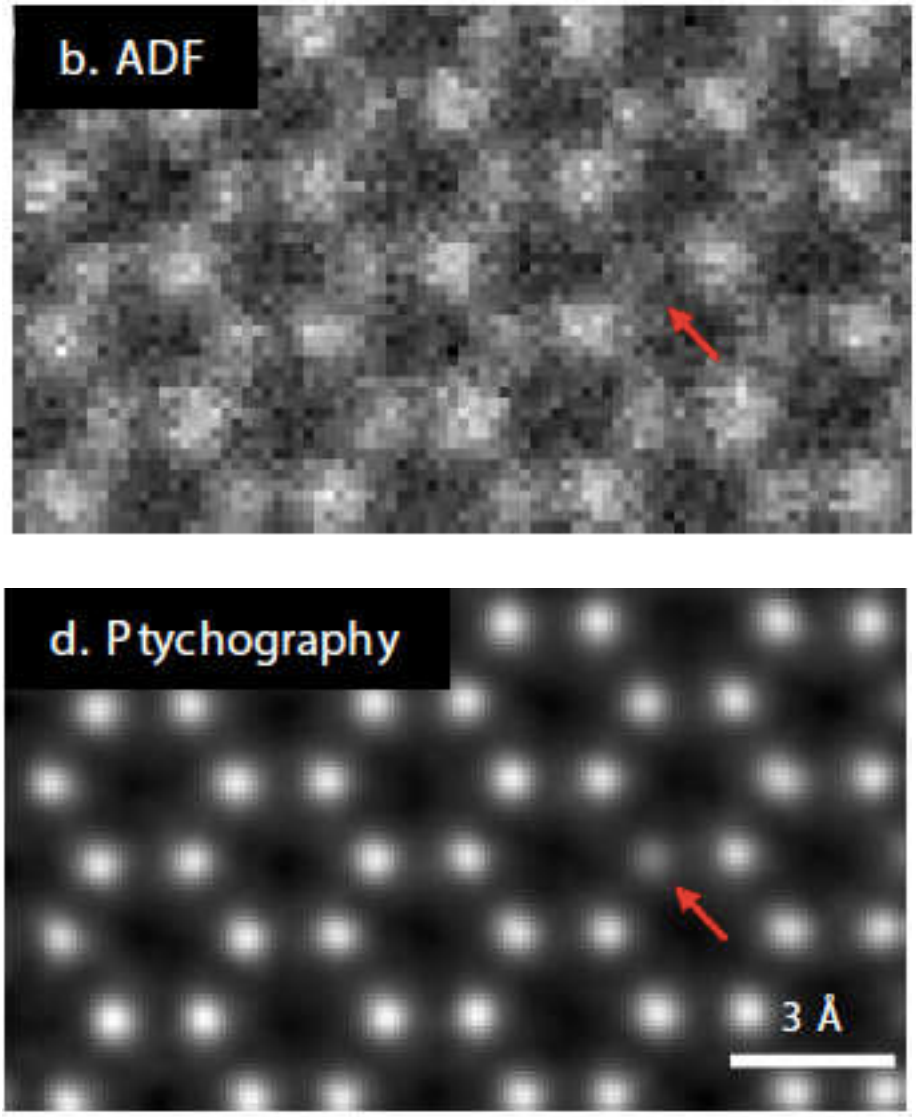

Figure 1 | Improving the resolution of electron microscopy. a [currently labelled ‘b’ – from paper], This image of a sheet of molybdenum disulphide was obtained using annular dark-field electron microscopy — the conventional method of incoherent imaging used for very high resolution. **b [currently labelled ‘d’ – from paper]**, Jiang *et al.*[1] report an electron microscope that works by analysing the diffraction patterns of electrons that have been transmitted through a sample (a technique known as ptychography). The method provides the best resolution yet reported for an electron microscope. Here, the atoms in the sheet of molybendum disulphide are much clearer than in **a**.