

Rearranging Crystals from Within

Julian Klein and Frances Ross explain how electron microscopes are becoming tools for engineering defects inside crystalline materials.

By Akashni Raghobar Latchanna

Electron microscopes are windows into the atomic world, creating images that can reveal the atomic arrangements within biological tissues or crystalline solids. But the electron beam that unveils this hidden world also changes it—sometimes in damaging ways.

Many researchers therefore consider beam-induced changes as an undesirable nuisance. But Julian Klein, a physicist at MIT, sees them as an opportunity. A few years ago, while studying a magnetic semiconductor called chromium sulfur bromide (CrSBr), he noticed that the atoms inside this material seemed unusually prone to shift under an electron beam. Klein wondered whether such a beam could be used to shift the atoms deliberately.

Klein worked with Frances Ross, an expert in electron microscopy at MIT, to control the positioning of electron beams with picometer-scale precision. They and their colleagues have

now used these highly controlled beams to reposition large numbers of atoms deep within a crystal [1]. The work suggests a route to designing materials with desired electrical, optical, or quantum properties. Klein and Ross spoke to *Physics Magazine* about developing this technique and why it's a thrill to watch a material being built up before your eyes.

All interviews are edited for brevity and clarity.

Why are you interested in moving atoms around in a material?

Klein: When atoms are displaced, they leave imperfections—or defects—in the crystal. A single defect can have interesting, localized properties. It might, for example, emit photons or respond to magnetic fields. To obtain such functions on a larger scale, researchers can add multiple imperfections to a material, but the actual locations of these defects are often left to chance. We wanted to see if we could provide control over defect locations by precisely manipulating atoms inside a crystal structure.

Why use an electron microscopy beam for this matter engineering?

Ross: From the earliest days of electron microscopy, microscopists realized that the electron beam alters the sample's structure. As microscope performance improved, with finer beams and more precise steering, it became possible to target individual atoms and make those changes deliberate. Often, this engineering has been done on the surface of materials. But surface atoms are exposed and delicate, often requiring low temperatures and high vacuum to stay in place. What we are showing now is a way to move atoms within a



Credit: F. Ross and J. Klein/MIT; C. Cain/APS

crystal, creating materials that are more robust.

What was the hardest technical step?

Klein: There were several. First, we needed a material that would respond to the electron beam in a useful way without being destroyed. CrSBr turned out to be very amenable to these changes. The other big challenge was delivering electrons to exactly the right place. In collaboration with Kevin Roccapiore at Oak Ridge National Laboratory in Tennessee, we developed approaches that let us position a focused electron beam with a precision of 20 picometers, which is only a fraction of the spacing between atomic columns.

How does the electron beam move an atom?

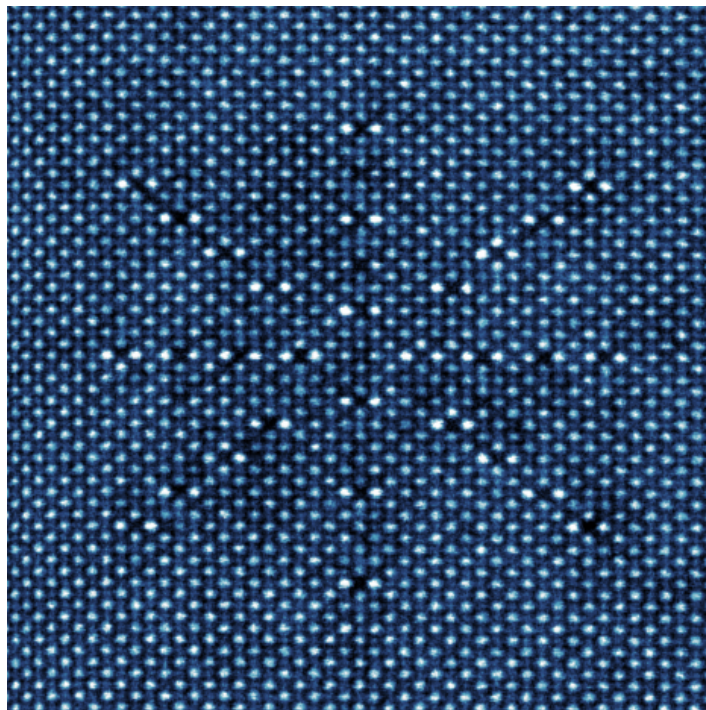
Klein: The important thing is that we are not exposing the whole material to the beam and watching random damage occur. We first position the focused electron beam on a single atomic column within the crystal lattice. In CrSBr, the chromium atoms are unusually responsive to the electron impacts. We found that a back-and-forth scanning motion of the electron beam could cause a targeted chromium atom to transfer into a nearby site, leaving a vacancy—or defect—in the crystal. This controlled movement was not limited to a single atom; it occurred for several atoms along the same column. That was the key step: showing that the beam could produce a controlled local rearrangement, while preserving the surrounding crystal enough to create the same kind of defect again and again. That was when it became clear to us that our method offered a way to engineer the crystal locally and repeatedly.

How many atoms can you move?

Ross: In a 40-minute trial, we moved 40,000 atoms within a CrSBr sample, creating an extended array of vacancy defects. The method could conceivably be scaled up even more. We can imagine quickly building configurations of millions of defects in programmed arrangements. Scalability has been a limitation in quantum science, so we are excited to see what can be achieved.

How do you know that the atoms have gone where you directed them?

Ross: We can see changes of brightness in the electron-microscope images. That's the great thing about electron microscopy. It can provide a [movie](#) of what's happening when a crystal grows or when a metal becomes an



Using an electron beam, Klein and colleagues are able to reposition chromium atoms in a CrSBr crystal. As a demonstration of their precise control, the team created this star-shaped pattern.

Credit: J. Klein/MIT

oxide. The “wow” of a material doesn’t only come from looking at the outside. There’s just as much wow on the inside.

What new physics could this capability make accessible?

Klein: We are not limited to periodic structures. We can deliberately introduce disorder or inhomogeneity, structures that the human mind might not intuitively design. Those arrangements could yield interesting magnetic, optical, or electronic effects. They may also allow us to explore elusive quantum phases or collective states.

Does this work bring us closer to science-fiction materials, like the ultraresistant armor that the superhero Iron Man wears?

Ross: We are still far from structural materials that you could hold in your hand or use to deflect a death ray. But what is more plausible is redesigning materials for computers and other information-processing devices. If we can control the electronic

or optical functions of the materials, we might potentially make those devices more brain-like, more portable, and less power-hungry. There are also exciting possibilities in using these engineered materials to perform quantum simulations of other complex systems.

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REFERENCES

1. J. Klein *et al.*, “Mesoscale atomic engineering in a crystal lattice,” *Nature* **653**, 715 (2026).