

formed its own colloids, which it can do under some circumstances. Some of the colloids present are typical of those that can, in the presence of water, spill off the waste glass formed by a nuclear explosion.

Kersting told us that there is some concern that the pumping of groundwater out of the well may have increased the proportion of colloids in the water. This summer, her group plans to study the water flow through fractures without pumping to understand the natural concentration of colloids in different groundwaters.

There are many other questions that need answering. How reversible is plutonium sorption onto various colloids? How far can colloids travel in groundwater? Does the low concentration of plutonium observed at the Nevada Test Site sampling wells reflect the long distance traveled, a low concentration of plutonium incorporated into the waste glass at the explosion site or a low concentration of plutonium absorbed onto naturally occurring colloids in the underground flows? Did the nuclear explosions at the Nevada Test Site create fractures that facilitate groundwater flow, or did they merely amplify the effect of fractures already occurring naturally at the site?

Applicability to other sites?

Of course, one of the largest questions is whether the finding at the Nevada Test Site is applicable to other types of waste and to other disposal sites, where the geology and hydrology may be considerably different. Of particular concern are the Hanford Nuclear Reservation near Richland, Washington, where, for many years, plutonium-containing waste has been buried in trenches or stored in leaky million-liter storage tanks, and Yucca Mountain in Nevada, where DOE is exploring the establishment of a permanent repository for spent fuel rods from nuclear power plants and nuclear waste from defense operations. (See the special issue on radioactive waste, PHYSICS TODAY, June 1997.) Although so far there are few data for assessing the possibility of colloidal transport at the Yucca Mountain site, planners there are including all possibilities. Just last December, the DOE released its *Viability Assessment of a Repository at Yucca Mountain*—a report mandated by Congress—which was the first such analysis to include potential plutonium transport by colloids in estimating the possible future radiologic contamination.² Abe van Luik of the Yucca Mountain Project, who heads the total system performance analysis (TSPA), which is covered in chapter 3 of the report, told us that the inclusion of

colloidal transport made a difference; in TSPA models, plutonium made a major contribution to the radiation dose at a point 20 km from the repository, but only some hundreds of thousands of years after burial.

Like the analysts at Yucca Mountain, researchers at other DOE sites where nuclear waste is stored are studying aspects of colloidal transport. The concern is not limited to transport of plutonium. For example, quite a bit of cesium and other radionuclides has moved unexpected distances from storage sites where containment has failed. Preliminary work suggests that transport was facilitated by the makeup of the solutions in which the contaminants were disposed, but colloidal contributions have not been ruled out. Van Luik cautions that “care must be taken in using the data or insights from

one location, waste stream or radionuclide to make assumptions about phenomena at other locations.” Nevertheless, he adds, researchers working on various aspects of radionuclide transport can learn from one another.

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Low-Energy Electron Beams Modify Semiconductor Surfaces

It is a truth universally acknowledged—at least in quantum mechanics—that you can’t observe something without changing it. But, until recently, it’s been widely assumed that the low-energy electron beams that form the basis of low-energy electron diffraction (LEED) and Auger electron spectroscopy (AES) do not significantly alter clean semiconductor surfaces.

Testing this conventional wisdom, the University of Minnesota’s Koji Nakayama and John Weaver found that, in fact, electron beams do create defects on silicon and gallium arsenide surfaces.¹ Their results not only emphasize that LEED and AES should be used with care, but also hint that electron beams could be used instead of chemicals to etch semiconductor surfaces.

Electrons as surface probes

In LEED, electrons are fired perpendicularly at a surface to probe its symmetry and structure. The electrons diffract because the energies they’re accelerated to—typically 5–500 eV—confer wavelengths that are about the same size as the atomic separation at the surface.

To bounce back from a surface, electrons must interact strongly with it. In doing so, they careen off more than one surface atom—with or without losing energy. Determining surface structure from a LEED diffraction pattern, therefore, is tricky. Indeed, from Clinton Davisson and Lester Germer’s original 1927 demonstration of electron diffraction, it took 40 years for theorists to

Recent experiments suggest that electron beams could be used to pattern semiconductor chips.

forge and hone the requisite mathematical tools.

Nowadays, thanks largely to this theoretical investment, LEED is one of the most successful techniques for determining quantitatively how atoms are arranged on a surface.

Like LEED, AES also exploits electron beams, but in a different way. Electrons are fired at a surface to provoke the ejection of atomic electrons through the Auger process. Analyzing the resulting electron spectrum reveals the identity and number of the atoms on the surface. If you want to know what impurities are covering a surface, AES is your tool.

Nakayama and Weaver did not set out to examine the limitations of LEED and AES. Rather, the focus of their investigation was etching.

In dry etching, halogen atoms are wafted onto a semiconductor surface, where, like lions preying on a herd of zebras, they separate and seize the most weakly attached surface atoms. Electron beams aren’t generally used as etchants, but, as observed first by Paul Redhead² and Dietrich Menzel and Robert Gomer,³ they can pry loose gases adsorbed on metallic surfaces.

To find out whether electrons would aid and abet halogen etchants, Nakayama (who has just moved to Tokyo University) decided first to as-

certain what electrons could do by themselves. He prepared a contaminant-free Si(100) surface, examined it under a scanning tunneling electron microscope in ultrahigh vacuum (5×10^{-11} torr), exposed it to the beam from a LEED electron gun, and then reexamined it under the STM.

Clear and extensive evidence of surface modification prompted Nakayama and Weaver to study the effect systematically for a range of surfaces, exposures, doping levels and electron energies. The figure on this page exemplifies the data they collected.

In general, it appears that electron irradiation promotes the proliferation of some of the same sorts of defect that are present in small concentrations on pristine surfaces and larger concentrations on etched surfaces. For the Si(100) surface, these defects are principally dimer vacancies, which involve pairs of missing surface atoms, and so-called C-type defects, whose nature remains to be definitively established. Under exposure to 2000-eV electrons, the density of dimer vacancies increased almost sevenfold.

Nakayama also exposed Si(111) and GaAs(110) surfaces to electrons. The density of defects on those surfaces increased, too.

How exactly do the incoming electrons knock out surface atoms? Weaver proposes that inelastic cascade scattering is responsible. As they bounce off atoms, electrons are captured at antibonding surface resonances (surface potential wells). To accommodate the captured electrons, the atoms reconfigure by moving further apart, which makes it possible for atoms to desorb, move onto a terrace or do both.

According to Ted Madey of Rutgers University, experimentalists have known (or should have known) for many years that energetic electron beams induce electronic excitations that can damage monolayers of gases on surfaces and the surfaces of many compound materials (like oxides). "What's new here," points out Madey, "is the recognition that even elemental semiconductor surfaces can be damaged, and with relatively high probability."

Reassuringly, Klaus Heinz (University of Erlangen-Nürnberg) doesn't think the consequences for LEED are disastrous. Heinz explains that LEED is a "forgiving method," in that only well-ordered patches on the surface contribute to the diffraction spots. Defects end up in the diffuse background, which is routinely subtracted anyway. To check for electron damage, he recommends repeating the intensity measurement: "If the data of the repeated measurement agree with the

first data, things are okay."

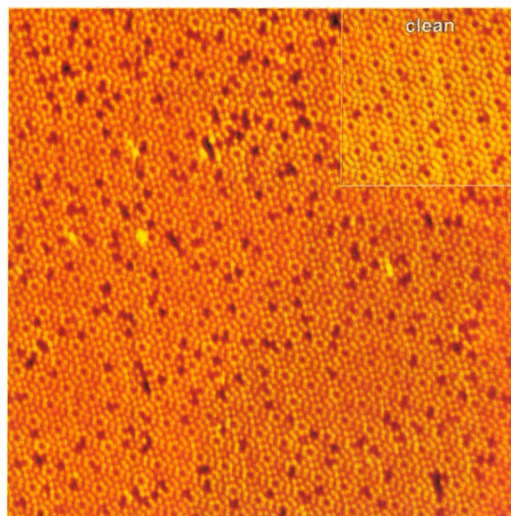
Evil, be thou my good

When Weaver first saw the postbombardment STM images, his reaction was, "Wow, that's neat!" His delight arose from the possibility that electrons could be used to deliberately modify semiconductor surfaces.

Weaver envisions that a kind of electron-photon tag team could pattern surfaces without using chemicals, which are often toxic and always have to be removed and disposed of when etching is complete. The electrons, thanks to their strong elastic and inelastic scattering, would broadly sample the energy landscape of the surface and crack open defects. Entering the ring next, a tuned laser could widen the defects by resonating with a desorption state.

The prospect is not fanciful. Last year, Hans-Joachim Ernst, Fabrice Charra and Ludovic Douillard of CEA Saclay demonstrated that lasers can induce atomic-scale restructuring of single-crystal copper surfaces.⁴ And Weaver's group has already demonstrated the tag-team approach for GaAs(100).

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BEFORE AND AFTER. The inset shows a scanning tunneling microscope image of a clean silicon(111) surface. The main panel shows the same surface after it was exposed to $2 \times 10^{16} \text{ mm}^{-2}$ electrons at 90 eV. The concentration of adatom vacancies increased by 50%. (Figure courtesy of John Weaver.)

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Is the Island of Stability in Sight?

Researchers from the Joint Institute for Nuclear Research in Dubna, Russia, and from Lawrence Livermore National Laboratory, claimed in January that they had produced element 114. The news raised hopes in many quarters that this sighting, like the appearance of a shore bird after a long sea voyage, might be a harbinger of the long-sought island of stability, a region populated by superheavy elements whose halflives might range up to hundreds or thousands of years. The reported atomic number of 114 is in the vicinity of the magic numbers associated with increased stability, according to most theoretical calculations. The alleged lifetime, while only 30 seconds, is still orders of magnitude greater than the halflives of isotopes produced to date in the atomic number range 109–112.

Reactions to the announcement are tempered by the need to confirm the result. The Dubna–Livermore group has seen only a single atom. Moreover, the researchers produced it in an

▶ Will a single nucleus turn out to be just what its discoverers think it is—a relatively long-lived isotope of element 114 lying in or near a region of very stable heavy nuclei?

unexplored region of the chart of nuclei, so one cannot link the daughters and granddaughters of its decay chain to any known isotopes.

An attempt to confirm the result is already in the offing. A team at Lawrence Berkeley National Laboratory has been planning all along to do the same experiment and will try for element 114 this summer. One of the long-time team members, Albert Ghiorso, was so enthusiastic about the prospect of reaching the island of stability that he confessed, "I'd trade five of the elements Berkeley has produced for this one from the Russians." Unfortunately, Glenn Seaborg, long-time leader of the Berkeley team, died on 25 February after suffering a stroke last summer.