Can electronics heal themselves?

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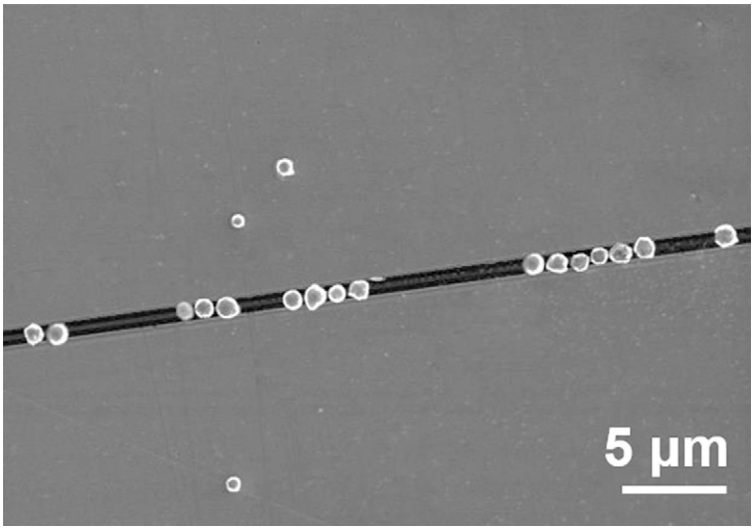
When someone gets a cut, white blood cells follow chemical signals to the site of the injury, fending off infection and promoting healing. Meanwhile, platelets rapidly crowd in to stop the bleeding. Collagen fills the wound.

If electronic materials could heal themselves like living tissues, scars on all sorts of devices would fade. There would be fewer cracked cell phone screens. Self-healing electronic materials could boost the durability of wearable electronics. And electronics for distributed environmental and urban sensors, as well as implanted medical devices, could be refurbished autonomously, mitigating the need for difficult, risky, and costly replacements.

But if researchers are to invent myriad efficient, effective ways to allow electronics to heal themselves, a multitude of scientific and technical challenges must be addressed. Scientists have, for example, made scratch-resistant paints and crack-healing concrete coatings by mixing in capsules full of healing glues. But anything added to or released into an electronic circuit has to have the right electronic properties or it will impair performance even as it heals the physical crack. To get around these challenges and devise smart self-healing, some investigators are looking back to biology for inspiration.



A scanning electron microscope image captures spherical nanomotors migrating to a crack in order to restore conductivity. Image courtesy of Jinxing Li (University of California, San Diego, La Jolla, CA).

Electronic Immunity

That's precisely the strategy of chemical engineer Anna Balazs at the University of Pittsburgh. Balazs is attempting to build an artificial white blood cell to monitor and fix flaws in electronic materials; it would sense scratches or cracks, then travel to them and fix the problem. Early versions used capsules filled with healing nanoparticles. The capsules get stuck in cracks like a pebble caught in a sidewalk crack, then their thin shells burst, releasing the contents. In a proof-of-principle version, capsules found cracks in a polymer surface and released cadmium selenide nanoparticles (1). The group chose this combination of materials to validate what had been shown in computer simulations: that a cell-like capsule could find and be activated by a flaw.

Since then, Balazs has been improving on the concept. Because this early version couldn't move autonomously, it was only a first step toward an electronic immune system. But Joseph Wang, director of the Center for Wearable Sensors at the University of California, San Diego, saw Balazs' work and wondered if the solution might be nanomotors: tiny particles of different shapes and composition that can move on their own. Wang's nanomotors use various methods to zip around, depending on where they need to go. Some are guided along by external magnetic fields or light; others consume chemical fuels to produce propulsive gases.

Balazs and Wang started collaborating, and showed that self-propelling, conductive nanomotors could land on a scratch in a gold electrical line, fill in the gap, and restore conductivity (2). In one demo the repairing particles fill in a flaw in a circuit connected to an LED, and the light comes back on.

Wang chose a known nanomachine design for the healing task: gold-platinum nanomotors fueled by hydrogen peroxide. One hemisphere of the gold particles is coated with platinum, which catalyzes the breakdown of hydrogen peroxide. In objects that are on the centimeter or millimeter scale, this reaction generates propulsive oxygen bubbles, an effect first described in 2002 (3). In 2004, Thomas Mallouk showed how the same reaction could propel a gold-platinum nanoparticle, but in a more complicated way; at the nanoscale, different forces become more important (4). As the hydrogen peroxide fuel breaks down, this creates a local oxygen gradient. That gradient generates an electric field that in turn drives a flux of positive ions along the particle surface from the platinum side to the gold. These cations are the nanomotor's "oars" and pull the particle forward.

Wang's nanomotors propel themselves around randomly, but as in Balazs' early designs, they get caught in

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A mannequin in Joseph Wang's laboratory shows off several printed electronic devices, along with a T-shirt, headband, and a swimsuit carrying panels of sensors. The mannequin's arms and collarbone are stuck with electronic tattoos.

flaws in an electrical circuit and aggregate, something like platelets in blood. The next step is to make the nanomotors more attracted to the circuit "wound," says University of Pittsburgh postdoctorate, Oleg Shklyaev. Balazs' group is exploring whether applied electric fields might fit the bill.

Wearing It Well

The biggest near-term demand for self-healing electronics may be wearables, a growing list of advanced accessories that can, among other things, monitor vital signs. "Wearable electronics are leading to increased interest in self-healing materials," says Zhenan Bao, a chemical engineer at Stanford University. Electronic wearables pose new kinds of wear-and-tear challenges that a conventional processor—safely packaged inside a rugged, rigid casing—doesn't face. Worn on the clothes or the skin, these devices might get ripped, cut, or abraded.

At Wang's laboratory, a casually dressed mannequin makes a good case for why self-healing electronics have a real market. It shows off several printed electronic devices made by the University of California, San Diego laboratory: a t-shirt, headband, and even a swimsuit carry panels of sensors, and its arms and collarbone are stuck with electronic tattoos. These all are demo versions of wearable sensors that carry out continuous health monitoring, the sort usually done via an occasional blood or urine sample at a doctor's office. These versions can measure metabolites, like lactate and glucose, pH, hormones, and more. Nearby sits an athletic mouth guard fitted with sensors that can monitor levels of uric acid, cortisol, and lactate in saliva. Such gear could monitor vital signs of the elderly or notify a coach that it's time to pull a player off the field.

Bao is developing an even more intimate sort of wearable that requires maximal durability: self-healing materials for electronic skin. These flat, stretchy sheets of sensors will wrap future prosthetic limbs and help robots pick things up. While Wang and Balazs use nanotechnology, Bao's approach is to tailor molecules.

Counting on Chemistry

Self-healing systems that rely simply on chemistry have had some flaws, notes Bao. Some use weak hydrogen bonds to bring cut pieces back together, but these are sensitive to moisture in the air. Others that break and reform through the creation of strong bonds need to be heated or exposed to UV light. Bao is trying to make simpler self-healing materials. Recently, she made a super stretchy, self-healing artificial muscle material by tailoring the chemistry of a commonplace malleable polymer, known as PDMS (5). This material might act as an actuator for a robotic arm, for example. But the same self-healing chemistry could be used to make wearable electronics or prosthetic skin. Bao added iron centers that rapidly bind to other ligands added to the polymer. These easy-come, easy-go bonds reform very easily after the material is cut or punctured.

Now the Stanford group is working on expanding their materials kit to make the full palette of materials needed for self-healing, active electronics such as transistors. Self-healing conductors need a complement of other materials like semiconductors and insulators. Balazs says the nanomotors can carry different materials too, not just metal.

For any of these projects to make it to market, researchers must find their way over multiple hurdles. Not only must these new materials be self-healing, for example, they also have to have the right electronic properties to substitute for existing materials such as silicon. It's about more than just making one-off molecules, says Bao. "The goal is to develop new materials design concepts to make multifunctional electronic materials," she explains. In the end, nature may provide the solutions for perfecting self-healing in these electronic artifices. "Biology," says Balazs, "has provided a solution to this problem for thousands of years."

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