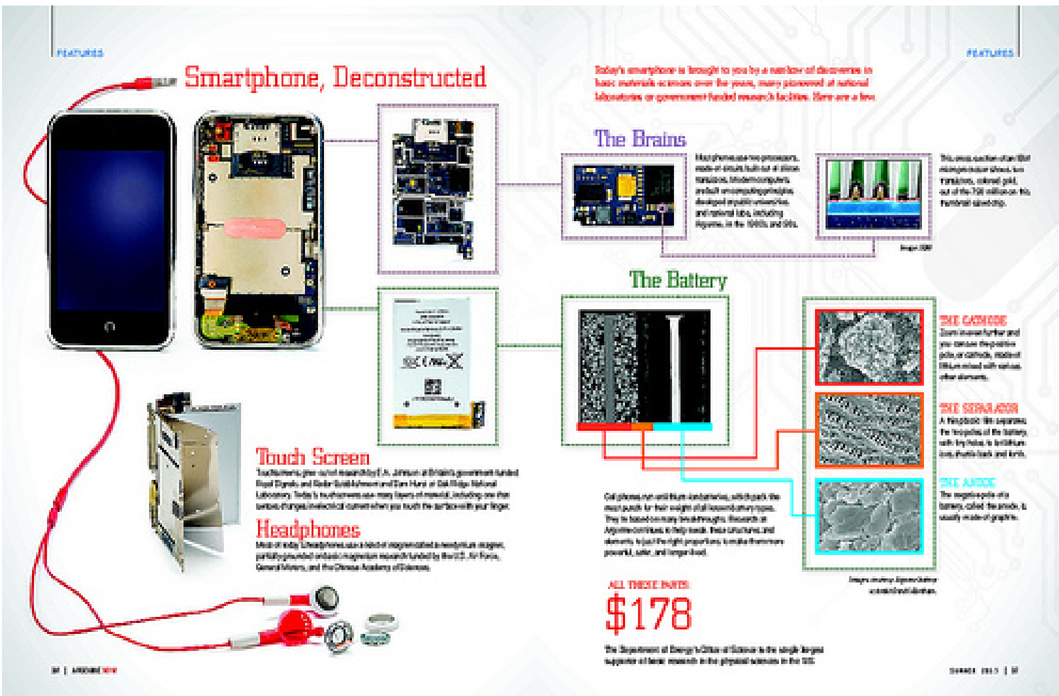
How your smartphone got so smart

September 16 2013, by Louise Lerner



Today's smartphone is brought to you by a rainbow of discoveries in basic materials sciences over the years, many pioneered at national laboratories or other government-funded research facilities.

In 1947, the Cold War, David Letterman, and the CIA were born; the future Queen Elizabeth got married; and a U.S. postage stamp cost 3 cents. That was also the year the seed that would eventually grow into smartphones first took root.

The seed didn't look that impressive, at least not next to the flashier rockets for outer space that other scientists and engineers were building at the same time.

Three scientists at AT&T's Bell Laboratories in New Jersey were tinkering with a device that would turn an electrical signal on and off. The dime-sized contraption, cobbled together out of germanium and gold, turned out to be the reason why you can get email from a person halfway around the world, look up restaurant reviews on your phone, and get driving directions from your car.

Today, we know this device as the transistor. Transistors form the basis of modern electronics; we stamp out millions at a time, and they could all fit on the end of a pin.

It's not much of an exaggeration to say that the transistor changed the world.

Before the transistor, TVs and radios ran on vacuum tubes. These were hard to manufacture and hard to miniaturize (the world's first general-use digital computer weighed 30 tons), partly because they depend on maintaining a perfect vacuum.

Once transistors took off, though, electronics never looked back. Scientists quickly figured out that silicon was the perfect material for transistors—it made cheap, precise, and easily miniaturizable devices. In the latter half of the 20th century, the potential for better electronics seemed virtually limitless. In fact, in 1965 a scientist named Gordon Moore predicted that the number of transistors on a computer chip would double every two years, and Moore's Law has been remarkably accurate through the present day.

As transistors got smaller and smaller, computers performed more and more calculations per second. This let engineers pack unbelievable computing power into smaller platforms. Silicon transistors are why computers could shrink down from the monsters that occupied entire rooms in the 1940s into the sleek laptops of today.

The tiniest transistors are now less than 30 nanometers long. You could fit 16,000 of them, side-by-side, in the period at the end of this sentence.

But like all things, the reign of silicon transistors must end.

A transistor is really a glorified on/off switch. When it's "on", it allows current to flow through. When it's "off," the current stops. This is the language of computers: 1 (on) and 0 (off).

As they get smaller, silicon transistors get less efficient. The barriers separating "on" from "off" are so thin that the transistor never quite turns completely off, and it starts to leak power. It's like trying to dam a stream of water with your hand; most of the water stops, but a little still trickles through.

In electronics, power is lost as heat; leaky transistors are one reason why laptops run so hot. Much of the engineering in computers, from your phone to the largest supercomputers, revolves around cooling the chips. In fact, in terms of watts emitted per square inch, a transistor is comparable to a nuclear reactor.

"At some point, we'll hit the limit, and we won't be able to cool the transistors fast enough," said Anand Bhattacharya, a physicist at Argonne. "The answer almost certainly lies in a new class of materials to replace transistors."

Transistors, and everything else in your smartphone, are the domain of a field called "materials science."

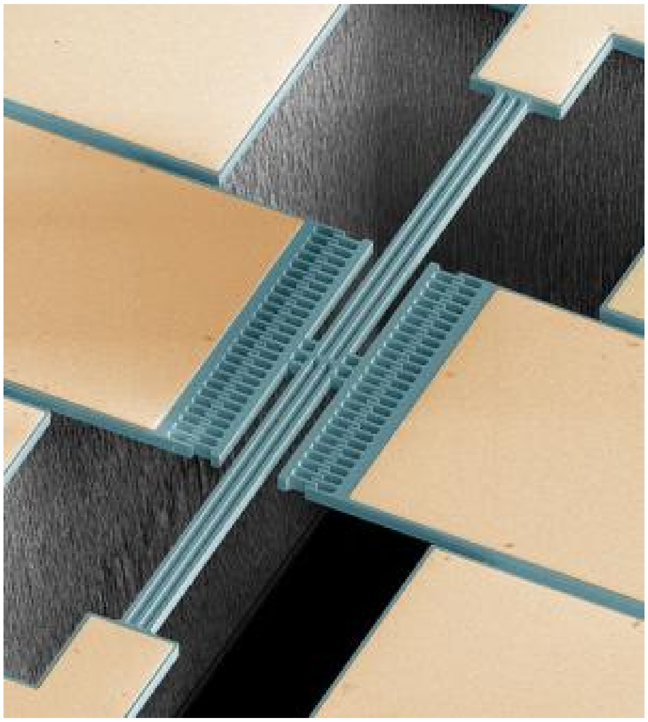
Materials science is the field that takes discoveries in physics and chemistry and uses them to arrange atoms to do what we want them to do. Blacksmiths, among the earliest materials scientists, melted iron and charcoal together to make steel. Egyptian materials scientists found that melting sand and something alkaline made glass.

New materials transform the world. We categorize our past according to what materials we could make: the Stone Age, the Bronze Age, the Atomic Age. The hunt for the next round of miracle materials will give us faster, cheaper, and smarter electronics, as well as everything from affordable solar panels to batteries that power cars for 300 miles.

Inventing a material today is a bit more complex than it used to be. Our electronics have gotten so sophisticated that in order to create a new material, we have to know what it looks like at incredibly fine detail—at the level of molecules and atoms. To do so, scientists have several ways of getting pictures of what's happening down there, even though it's far too small for human eyes to see.

One way is to use incredibly powerful X-rays, like those at Argonne's baseball stadium-sized Advanced Photon Source, to shoot X-rays at a sample. When the beams hit and scatter in all directions, scientists piece together the information to recreate a "picture" of the material at nearly atomic detail.

Sophisticated computer models can predict behaviors of unknown materials; running them on a supercomputer, like Argonne's IBM Blue Gene/Q Mira, lets scientists combine millions of data points for the most accurate models. They run thousands of simulations of different ways to combine chemicals. Once the computer spits out a few interesting answers, they can take those to the lab to confirm the results.



Technology like this tiny microelectromechanical system resonator, fashioned at Argonne's Center for Nanoscale Materials, could soon make clocks more accurate. Credit: Daniel Lopez / Argonne National Laboratory

"Our ultimate goal would be the ability to custom-tailor a new material—building it atom by atom to suit our purposes," said Argonne senior chemist John Mitchell. "There's no one clear road to a successor to the transistor, but there are several bright prospects."

Oxides

Scientists at Argonne are looking at interesting materials called Mott insulators, which could eventually knock silicon off its pedestal.

Mott insulators are a curious class of materials. Conventional theory predicts that they should conduct electricity, but when scientists tested them, they found the materials were actually insulators. Many in the field believe that if we could find the right recipe, we could build Mott insulators that flip back and forth between conducting and insulating when a voltage is applied.

The problem is that we don't understand the basic physics behind Mott insulators nearly as well as we do silicon; we don't know enough about them to harness them. Until last year, no one had built a working Mott-based transistor. A team of Japanese scientists managed to make build a prototype in 2012, which set the materials world buzzing, but it only worked partially, and the conditions they used aren't really practical for a working smartphone or computer. So the race is still on.

Mott insulators are made out of transition metal oxides: metals from a particular section of the periodic table (like copper, manganese, or iron) with oxygen added.

"What we have to do is learn to understand and control a material fairly well, and then we explore how they behave under different conditions," said Bhattacharya. "We look for new and exciting properties that pop up when we arrange atoms in different ways."

To study them, Bhattacharya designed a very useful device at Argonne called the molecular beam epitaxy machine. It looks a bit like a smaller Apollo lunar module: a large metal cylinder with a dozen smaller tubes feeding into it.

Each tube contains a different metal. The tubes have exceptionally precise shutters that release just a few atoms of, say, strontium. The strontium reacts with oxygen atoms in the chamber and forms a crystal layer. Working this way, scientists can build very precise layered materials, like a birthday cake with layers just atoms thick, and then test them to see how they work.

"Oxides can do things that silicon can't do," Bhattacharya said. "For example, they can change to be magnetic or not magnetic, or even to be superconductors."

Either of these properties could represent "on" and "off." In fact, other scientists at Argonne are looking at extending these ideas further.

Magnets

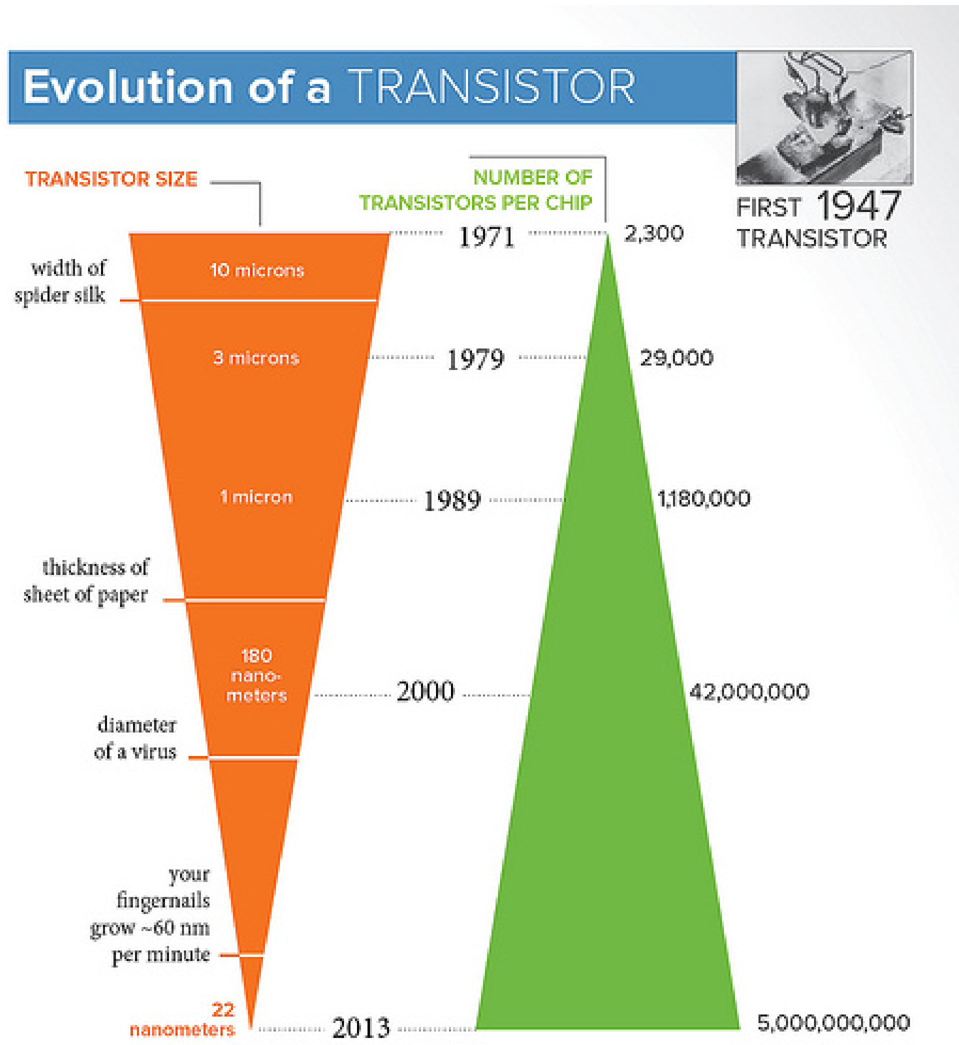
Magnets are already the magic behind loudspeakers, from the tiny ones inside earbuds to the big ones in amps at concerts. But if experiments pan out, they might become the backbone of electronic computing as well.

German scientist Peter Grünberg spent a year and a half as a visiting scientist at Argonne in the 1980s studying magnetism. He wanted to know what would happen if he alternated extremely thin layers of magnetic and non-magnetic materials. Argonne staff built him some prototypes using a process similar to molecular beam epitaxy.

Grünberg took the samples back with him to Germany and continued studying, discovering an effect called "giant magnetoresistance." When he applied a magnetic field, the magnetic layers aligned themselves parallel to one another, accompanied by a dramatic change in the material's electrical resistance. This switching, too, could be used to transmit on or off.

Giant magnetoresistance represented a breakthrough in materials science and permanently transformed the field. "Less than ten years later, IBM was selling the first hard disk drives based on the effect, and Grünberg went on to share the Nobel Prize," said Sam Bader, a physicist and Argonne Distinguished Fellow who worked with Grünberg.

While giant magnetoresistance was only used to read stored information on computers (and the original iPods) some scientists are imagining entire logic systems based on magnetism instead of silicon transistors.



By the 1970s, computer chips had 2,300 transistors that were each 10 microns across (about the width of spider silk). In 2013, the smallest transistors are just 22 nanometers and there are 5 billion on one computer chip.

"Magnets have all sorts of interesting properties for electronics," Bader said. "For example, they are non-volatile, meaning that they don't use power to maintain stored information; the data remain even if you turn off the device. Computers built based on magnetic logic, therefore, could boot up instantaneously."

Disk drives based on giant magnetoresistance, and other newly discovered magnetic effects, exploit a property of electrons called spin. Electrons are either "spin up" or "spin down." Changing this property changes the material's conductivity without altering the actual atomic structure of the material.

"If we could figure out how to make a reliable solid-state memory, which has no moving parts, we could see a future where hard drives would cost the same but store 100 times more memory and work at least 100 times faster," Bader said.

Teeny machines

When you tilt your phone sideways, the picture re-orients itself along with you. How does your phone know?

Inside the case, microscopic machines sense the change in speed as you tilt the phone and relay the message to the phone's brain. The phone's compass, microphone, and clock all use these tiny machines, called microelectromechanical systems, or MEMS. Some are even small enough to be called nanoelectromechanical systems (NEMS).

MEMS are tiny mechanical machines, usually made out of silicon, that run in the neighborhood of 10 microns long—the diameter single red blood cell. NEMS are even smaller.

MEMS are interesting because they let electronics do all sorts of interesting things that transistors alone can't do.

Phones and computers have come a long way since the 1950s. The magic technology that makes this possible is the silicon transistor. But we can't keep up this pace of shrinking them forever - as they get smaller, transistors get less efficient and start to leak power as heat. Sooner or later the reign of transistors has to end.

"Putting MEMS and electronics together is a powerful combination," said Daniel Lopez, a nanomaterials scientist at Argonne's Center for Nanoscale Materials. "Basically, what you are doing is taking a computer chip and giving it eyes, ears, arms, and legs. MEMs allow transistors to interact with the real world."

For example, the device that tells the phone it's being tilted is called an accelerometer. The same accelerometer lets you play video games and even measure your car's horsepower and speed with remarkable accuracy.

MEMS already appear in a variety of devices. Since the 1990s, they have been embedded in your car's airbags to sense crashes the instant they happen. They also pick up data to activate anti-lock brakes. Many laptops have MEMS accelerometers that detect a sudden change in altitude (i.e., when the laptop is dropped) and adjust the hard drive in midair to prevent damage. Lopez and others at Argonne are developing MEMs that will eventually replace the quartz-based timekeeping system in clocks around the world.

Another bonus: "Because they are so small, they consume virtually no power," Lopez said.

At Argonne, scientists study NEMS and MEMS to find out new ways to make them smaller and better. The Advanced Photon Source can take pictures of the devices at nearly atomic resolution, which helps scientists like Lopez study the basic structures of the machines.

"The newest NEMS are so sensitive that they can measure quantum forces," Lopez said. "All of a sudden we can explore situations that we couldn't even imagine a few years ago. It's very strange world down there. In theory, you could make devices that are virtually frictionless and thus almost 100% energy efficient."

The "strange world" has many more surprises for us and the scientists who are delving into it. Our phones may be smarter today than 50 years ago, but like the three scientists at Bell Laboratories in 1947, we still stand gloriously unaware of what they'll be able to do after another 50 years of research.

Provided by Argonne National Laboratory