Print Your Next PC

FORGET BILLION-DOLLAR CHIP FABS. IF MIT'S JOE JACOBSON HAS HIS WAY, YOU MAY BE PRINTING CHEAP SEMICONDUCTOR CHIPS ON YOUR DESKTOP.

BY STEPHEN MIHM

AS JOSEPH JACOBSON IS FOND OF POINTING OUT, FOR ALL THE GAINS IN SEMICONDUCtor chip performance over the past few decades, a typical integrated circuit—the brains behind your computer—is still far too expensive for most people on the planet. "Look at the way [a chip] is made," he says, punching the air with one hand while directing a PowerPoint presentation with the other. Fabricating a high-quality logic chip like Intel's Pentium processor, he points out, takes "two weeks, seven days a week, 24 hours a day. Chip fabrication facilities like the ones that Intel has are a $1.6 billion tool. And there are very few people on the globe who can touch that tool."

Jacobson's solution: a "desktop fab" able to print circuits directly on a substrate, such as plastic, without the expense and hassle of a multibillion-dollar manufacturing facility. Jacobson, head of the Printed PC Group at MIT's Media Lab, has already managed to print rudimentary but working transistors using an "ink" consisting of nanometer-sized semiconductor particles. "Our goal is to follow the trajectory silicon took, and start printing processors with perhaps several hundred transistors, moving to thousands and then more," says Jacobson. "We should be able to demonstrate a very simple processor in the next 12 to 18 months." And he predicts that printed logic chips with the speed and power of a Pentium could eventually be possible, making microchips available for a fraction of the time and expense associated with conventional manufacturing.

PHOTOGRAPHS BY KATHLEEN DOOHER

Flexible future: Bendable chips printed on a plastic substrate could be cheap and easy to customize.

If Jacobson's vision becomes reality, it could change everything in computer hardware. Printed electronics could be cheap enough to find their way into everything from "wallpaper" able to display changeable images to custom-designed logic circuitry. A chip fab on every desktop could bring about the day when individuals download the architecture of integrated circuits the way they download software today. It could, in short, transform hardware manufacturing much the way the "open-source" movement has changed how software is written. Indeed, at his most visionary, Jacobson contends printed logic could give rise to an open-source hardware movement where chips are custom-designed via the Internet and printed by the consumer in about the same time it takes to print out a Web page. You could, says Jacobson, "download the chip design from the Web, tie in some modifications from some guy in India, and boom—out comes the device."

It's lunchtime in Jacobson's lab, a windowless room with tangles of colored cable dangling from the walls and ceiling and a row of chemical hoods set along one wall. Jacobson's enthusiasm is contagious, and the cramped lab is obviously where he and his handful of students spend most of their time, even when they're eating. "What we're interested in is 'give me a piece of plastic and in a few seconds I'll give you back a Pentium,' or something of that complexity," he says between mouthfuls. "I'm serious about that. Not slower than a Pentium; indistinguishable from a Pentium."

Coming from almost anyone else, such a claim would be hard to swallow. But the 35-year-old associate professor has the credentials to deliver the goods. After all, when Jacobson joined the Media Lab in 1996, his immediate ambition sounded nearly as outlandish. "I wanted to have a display [screen] that could be printed," Jacobson recalls. "I wanted something that was incredibly inexpensive, something that would look like ink on paper." Something, in other words, like "electronic paper."

His solution was a riff on research conducted at Xerox Palo Alto Research Center (PARC) in the 1970s, where researchers had created microscopic balls that were black on top, white on the bottom. An electric charge determined which side of the balls rotated upward. With some clever wiring, the balls could be made to form letters and words. Jacobson and a handful of MIT undergrads pushed the idea in new directions. Rather than making balls of two colors, they fabricated millions of tiny microcapsules, each containing a liquid mixture of oil, dark dye and tiny shards of white pigment. They then layered the material onto flexible plastic and sandwiched it between transparent electrodes on top and bottom. Depending on the charge applied, the white shards migrate toward the top or bottom of the sphere, and when activated in concert, the electrodes can force the ink into recognizable patterns.

The rest is the stuff of venture-startup legends. E Ink was formed in 1997 with several of Jacobson's students at the helm, and has since raised nearly $55 million in private financing, forming deals with the likes of Motorola and Hearst Publishing. Media and pundits alike have proclaimed the technology as the end of paper as we know it. But what got lost in all the buzz over electronic paper is that you still need electronics to drive the pixels (the ink) of the displays. The prototypes built thus far by E Ink continue to rely on traditional (read: not cheap) silicon chips to control the display. To reap the full benefits of the technology, you need cheap, flexible electronic circuitry. E Ink has recently partnered with Lucent Technologies, whose researchers have been working on ways to print organic transistors onto flexible plastic substrates. (The two companies hope to unveil a working prototype of the technology this fall.)

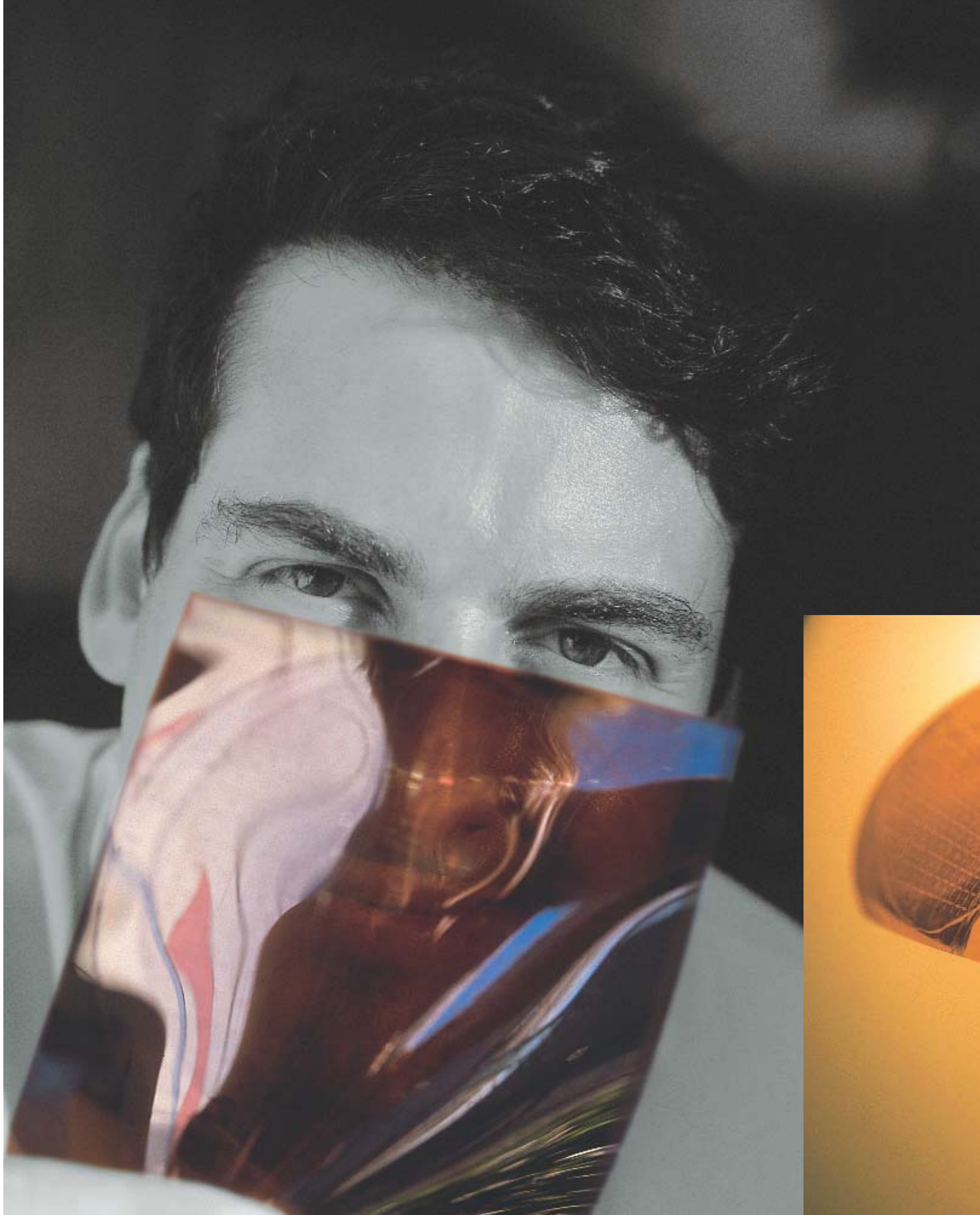
Jacobson, however, has even larger ambitions. Not only does he want to print the relatively simple electronic circuitry required to control a display screen, he wants to go the next step and find a way to fabricate high-quality logic on the order of a Pentium using similar printing methods. Not only would you be able to "print" your screen; you could, in a sense, print the PC itself—or at least its essential circuitry.

Inorganic Solution

MAKING A CHIP AS POWERFUL AS A Pentium by traditional means is not an easy feat. While semiconductor makers like Intel have learned to make transistors smaller and smaller over the past few decades, squeezing vastly more performance into the microprocessors, the basic mechanics of chip making haven't changed much. The base material remains silicon, sliced into thin wafers. An insulating layer of silicon dioxide goes on top of the wafer; a thin layer of "photoresist" (a light-sensitive material) is deposited on the silicon dioxide. Light beams project the pattern of the circuit onto the photoresist through a stencil; the pattern is then etched out by acids or reactive gases. Additional layers of silicon are added, "dopants" such as boron or arsenic are put into the mix, and finally the transistors are linked by means of tiny aluminum wires.

> A fab on your desktop could give rise to an open-source hardware movement where logic chips are designed via the Internet and then printed out like paper.

The resulting microchips are a marvel of engineering and are largely responsible for fueling the Information Revolution. Using multibillion-dollar manufacturing plants, Intel and others can now make transistors as small as a few hundred nanometers across (a nanometer is a billionth of a meter), packing tens of millions of them on a single chip. The downside is that the several hundred manufacturing steps take upward of two weeks



Printed prototypes: Jacobson holds circuitry made by stamping (left and far bottom) and using an inkjet printer (below).

and require clean rooms hundreds or thousands of times more pristine than your average laboratory.

Last fall, Jacobson and his student Brent Ridley described in the journal *Science* the first printed inorganic transistors. Several other research groups, most notably at Lucent's Bell Labs and Cambridge University in Britain, have also printed transistors. These groups, however, are using organic polymers; such materials could have great promise in the electronics required to make cheap, flexible displays. But organic transistors appear to be inherently limited in computing speed. Jacobson's big breakthrough is that he and his colleagues at the Media Lab have created liquid suspensions of inorganic semiconductors—the same class of materials used in your Pentium chip—so that they can be used in a printing process. In other words, rather than carving logic into a solid piece of silicon, Jacobson is simply printing it onto a substrate.

Jacobson's optimism is justified by his group's rapid advances in synthesizing "semiconductor ink." Under normal conditions, semiconducting materials such as silicon, cadmium selenide and gallium arsenide form bulk crystals with melting points well over 1000 C. Jacobson and his team, however, have found a way to synthesize a solution of tiny "nanocrystals" of 100 atoms or less. This semiconductor ink can be patterned or printed onto a variety of substrates, including thin sheets of plastic, at temperatures under 300 C. The particles, Jacobson notes, are small enough to form 200-nanometer structures—about the scale of complex integrated circuits like Intel's Pentium chip.

The suspension of nanoparticles is so similar to conventional inks that Jacobson and his co-workers are able to use an inkjet printer manufactured by Hitachi to fabricate tiny machines called MEMS, or microelectromechanical systems. MEMS, which are one of the fastest-growing new areas in materials technology *(see "May the Micro Force Be With You,"* TR *September/October 1999),* are typically made using many of the same arduous techniques used to fabricate conventional silicon microchips. Using the inkjet printer, Jacobson and his students have managed to fashion both a working thermal actua-

Jacobson's vision: Printed logic could change the meaning of "hardware."

tor and a linear-drive motor with features on the order of 100 micrometers by simply depositing hundreds of layers of ink. And they are able to form the tiny machines without a clean room and at temperatures well under 300 C.

The group has also used the inkjet printer to produce much more intelligent radio-frequency identification tags. Others are also working on such tags but are relying on logic using organic transistors. Jacobson thinks that the faster logic possible with inorganics can make his version of the tags far more intelligent, allowing companies to track everything from expensive goods to the packages in a supermarket. A radio signal detector could read the devices, update them and integrate them into inventory systems. A person could walk into a supermarket, pick up some items and walk out, and the money would be automatically tallied up and deducted from his or her bank account—and from the supermarket's inventory system.

Using printed circuitry like that is just the beginning. Because the computer logic is printed, it can be put on the surface of almost anything: soup can labels, textiles, soda cans. "You could add intelligence to almost anything you want," claims Colin Bulthaup, one of Jacobson's students. "One thing we want to do is build a digital camera in a business card: everything embedded into the card itself. There's no reason to have all these clunky silicon chips. You can pattern your semiconductor, your photodetector—all the materials together—and integrate them into a single device, one that is incredibly small, incredibly cheap and incredibly quick to produce."

But for now, printed semiconductor chips are far too slow for advanced logic applications. But soon Joseph Jacobson hopes to speed up the inorganic transistors.

Making such devices using an inkjet printer, however, is still a far cry from printing high-quality logic circuits. That requires fabricating transistors and other electronic components at the scale of a few hundred nanometers—the level of precision in a Pentium chip. For that, Jacobson has made use of polymer stamps that don't look all that different from the stamps used to certify documents. In one version, the stamp has the architecture of the circuit in positive relief and is dipped in the nanoparticle ink; the circuitry is then transferred by hand onto a substrate. Also promising is a negative stamp that "embosses" a thin layer of ink previously deposited onto a plastic surface. The stamp's features push aside the ink at certain points, forming whatever feature is engraved on the stamp at resolutions of 200 nanometers.

Pentium Challenge

THIS IS ALL A MIGHTY ATTRACTIVE VISION. BUT CAN PRINTED electronics actually compete with multibillion-dollar fabs in making the exacting circuitry needed for high-quality logic? Sigurd Wagner, for one, doesn't think so. A professor of electrical engineering at Princeton University, Wagner is also pursuing research into printed inorganic logic, but he sees its promise in cheap electronics that can be used over large surfaces, not in taking on high-quality microprocessors.

His goal, says Wagner, "isn't competing with integrated-circuit technology; it's to go into an area that traditional integrated circuits can't handle." Attractive applications include wallpaper that acts like a giant display screen, electronics woven into textiles—even "electronic skin" covering an aircraft that is able to respond mechanically to changing conditions.

Jacobson agrees that the short-term payoff will come in producing the cheap, flexible electronics that could make such applications possible. "There are a huge number of applications for incredibly inexpensive, low-power disposable logic on plastic substrates," he says. And for now, Jacobson's printed circuits are better suited for these uses. For one thing, they are still far too slow for advanced logic applications; while Jacobson's inorganic transistors are an order of magnitude faster than the printed organic transistors made by Lucent and other research groups, they're still 100 times slower than the best inorganic transistors made from conventional techniques.

But making tomorrow's Pentium-like chips on a desktop fab remains the twinkle in Jacobson's eye. That will take increasing the speed of the printed inorganic logic. It's "likely a several-year research project," he says, "but we believe it's doable."

It's just the type of challenge and hugely ambitious project that Jacobson relishes. It is the type of project that makes you rethink the possibilities of a very familiar object. With E Ink, he is giving a new twist to a very old invention—the printed page. Rather than throw out the newspaper, Jacobson wants to preserve its virtues while updating it for the information age. And now he's rethinking the fabrication of integrated circuits. If Jacobson can make his visions of printed circuitry practical, he could change the meaning of "hardware" and replace the multibillion-dollar semiconductor fab with something not so different from the stamps that have been around for thousands of years.

While the rest of the computing industry attempts to drive down hardware prices through mass production of a few standardized chips, Jacobson is going in the opposite direction, trying to make every person the master—and manufacturer—of his or her own logic. TR