# Small scale of transistors calls for REVIVAL OF A SILICON ‘RIVAL’

EE Professor Krishna Saraswat and MSE Associate Professor Paul McIntyre have used an atomic layer deposition machine hand-built by former student Hyoungsub Kim, to perfect transistors based on the element germanium.

BY DAVID ORENSTEIN

How is the element germanium like the early Soviet leader Leon Trotsky or the storied Apple CEO Steve Jobs? It too ushered in a revolution—microelectronics—only to be cast aside. Trotsky never returned to power. Jobs did. Electrical engineering Professor Krishna Saraswat’s goal is to reinstate germanium among the vanguard of the movement to produce transistors at the scale of a dozen nanometers.

“Germanium actually brought the microelectronics industry two Nobel prizes,” Saraswat says. “The first transistor made by Brattain, Bardeen, and Shockley at Bell Labs was germanium and the first integrated circuit at Texas Instruments by Jack Kilby was also in germanium. So why did we give it up?”

Well, two reasons. Silicon has always been the practical choice because it is abundant (and therefore cheap) and because it has a workhorse in its native oxide, $SiO_2$. An oxide provides the electrical insulation in tightly packed integrated circuits and “passivates” the surface of the semiconducting material. Passivation comes through a phenomenon in which the material ties up loose bonds on the surface of the semiconducting material that might otherwise trap electrons passing through, reducing electrical current (current is a flow of electrons). By contrast, germanium is rare and its native oxide, $GeO_2$, is thermally unstable and dissolves in mere water. Germanium is a much better conductor than silicon, but historically that virtue hasn’t overcome its vices.

That balance may now be tipping in germanium’s favor. For decades, chip makers have consistently shrunk transistors to pack more on each chip, making each chip more powerful. At the scale of a few dozen nanometers in length, however, silicon’s performance is starting to break down. Layers of $SiO_2$ insulation within the devices are becoming so thin (less than two nanometers) that current leaks through like oil from a corroded Alaskan pipeline. Meanwhile, the path the current is supposed to follow is becoming so narrow that not enough can get through.

These problems have led to calls for new materials and designs for future transistors smaller than 20 nanometers long. Saraswat has sensed for years that germanium could save the day, and recently his group's research has produced some compelling evidence.

## MATERIAL MATTERS

The first major step toward rehabilitating germanium's reputation was to discover a sturdy and effective "dielectric" material for insulating the gate of a germanium transistor. The gate is a metal electrode that delivers a voltage to either encourage or discourage current flow (the ability to selectively allow or block current flow is what puts the "semi" in semiconductor). The gate needs excellent electrical insulation from the germanium channel to control the current flow through it without becoming an unintentional path for current leakage.

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Saraswat's group, including materials science and engineering Associate Professor Paul McIntyre, has found that either a layer of zirconium oxide, hafnium oxide, or combined layers of germanium oxynitride and these oxides can insulate the gate on a germanium transistor with a performance and manufacturing practicality never thought possible. In germanium transistors using these oxides, very low leakage currents occur simultaneously with conduction that's better than in silicon. The insulating layers in the gates of the germanium transistors allow less leakage because they are physically thicker than the 2 nanometer $SiO_2$ layer in a conventional transistor, but in terms of encouraging current flow, they work better because of their superior "dielectric" properties. Essentially they encourage more charge to flow through the channel than a $SiO_2$-insulated gate of the same thickness would.

The group's first experiments were made possible largely through the enterprising work of former doctoral student Hyoungsub Kim, now a professor in Korea, who built an atomic layer deposition machine in McIntyre's lab out of spare parts from the Stanford Nanofabrication Facility. The machine can deposit materials on a surface in layers as thin as an atom, a capability necessary for making the thin layers of gate-insulating dielectrics.

Much of the group's work demonstrating the promising performance of germanium and its newfound oxides is summarized in two July 2006 papers in *IEEE Transactions on Electron Devices*. They essentially comprise the doctoral thesis of former PhD student Chi On Chui, now of Intel Corp, Saraswat says. "His work was so remarkable that it was included as a review paper in the journal," Saraswat says. "These are what we have done in the last few years, going back to 2002."

## TRANSISTORS TRANSFORMED

While Chui was working on insulating the gates of germanium transistors, another of Saraswat's doctoral students, Tejas Krishnamohan, was taking a parallel track, seeking for his thesis to combine silicon and germanium in new designs that could make the best use of each material. Recall that when germanium is supposed to conduct, it does so better than silicon. Electrons move through very quickly. The downside is that when germanium is supposed to shut off current flow, it doesn't do it as completely as silicon, leading to higher current leakage. If the two elements were road surfaces and charges were vehicles, then silicon might be asphalt and germanium might be ice.

What Saraswat, Krishnamohan, and the group realized was that they could design a transistor that took maximal advantage of the materials' relative merits and avoided their relative disadvantages. They conceived of a transistor with two gates —one on top and the other on the bottom of a channel consisting of a thin film of germanium flanked by silicon. In this transistor the electric field that pushes charges around is strongest at the edges and weakens to zero toward the center. By lining the edges of the channel nearest to the gates with silicon and laying a two-nanometer wide strip of germanium down the middle, they made a transistor that effectively insulates areas where the field is strong and still allows for maximum conduction in areas where the field is weak. In a sense, the silicon acts as a sort of guardrail for a highway of germanium.

"You get high 'on' current and low 'off' current, simple as that," Saraswat says.

In particular, transistors built this way with today's roughly 90-nanometer long channels showed a nearly 4.5 times improvement in conduction versus a silicon transistor of similar size, Krishnamohan, and the group wrote in a May 2006 paper in *IEEE Transactions on Electron Devices*. As for leakage current, Saraswat says, "we can reach pretty close to what is offered by silicon, within an order of magnitude." The higher current drive and roughly comparable leakage shows that germanium may yet have a renewed role now that microelectronics are really nanoelectronics.

Saraswat's group has shown through simulations that nanometer scale germanium transistors are clearly better than silicon, and in only a few years time germanium will be a serious player as a semiconductor. "It pays for us to selectively incorporate germanium where silicon cannot meet the demands of future technologies," Saraswat says. In other words, at this point in the revolution, silicon may have to share power with a long exiled rival.