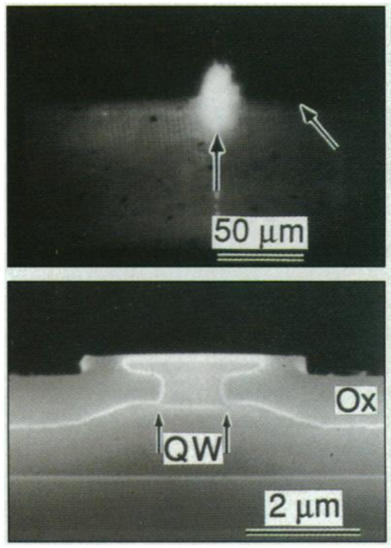
TECHNOLOGY

Light Guides May Help Optical Circuits Turn the Corner

For a speeding car on a winding road, each bend can be fatal—and the same is true for light in an optical circuit. Unlike the electrons of conventional circuits, light can't easily be routed around tight bends. And that's a flaw well worth overcoming, because in other respects light-based optoelectronic circuits combining lasers, optical switches, and other components on a single chip should be able to run circles around their electronic counterparts. But the tendency of optical "wires," called waveguides, to leak at sharp turns could mean optical chips will remain large and cumbersome, casting a shadow over the technology's use in high-speed switching, computing, and communication.

Things may have taken a turn for the better, however, after recent work by a group of researchers from the University of Illinois, Urbana-Champaign, and the Swiss Federal Institute of Technology in Zurich. This collaboration was able to build efficient curved waveguides in a gallium arsenide–based semiconductor, the staple material of optical circuits—the first time the feat has been accomplished. If it lives up to its promise, the achievement could free optical circuit designers from having to devote much of a chip's surface to gradual bends or rely on large external optical fibers. As a result, says Seng-Tiong Ho, an electrical engineer at Northwestern University, it could shrink optical circuits by factors of 10 to 100.

Even better, Ho says, the group's strategy—treating the semiconductor to create regions of altered refractive index—is "compatible with typical semiconductor processing technology." And that raises the prospect of mass-produced, integrated optical circuitry: the light-carrying equivalent of the integrated circuits that sparked the microelectronics revolution. The waveguide work, which the Illinois-Zurich group describes in the 10 April issue of *Applied Physics Letters*, doesn't just address "some little niche of the problem," says Thomas Koch, head of the photonic circuits research department at AT&T Bell Laboratories in Holmdel, New Jersey. Instead, "it's raising people's belief in [optoelectronic] technology" as a whole.

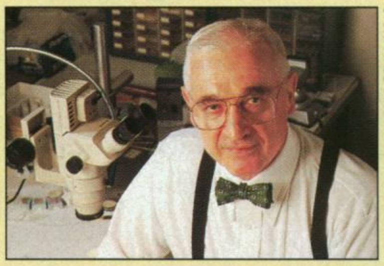


Tight confinement. Oxide layers *(above)* trap light within a waveguide *(top)*.

The group, which includes Michael Krames, Eugene Chen, Nick Holonyak Jr., Andrew Crook, and Thomas DeTemple at Illinois and Pierre-André Besse in Zurich, began with a quantum-well heterostructure (QWH), consisting of a layer of gallium arsenide sandwiched between layers of aluminum-gallium-arsenide. Unlike silicon semiconductors, gallium-arsenide–based materials

Japan Prize Honors LED Pioneer's Bright Ideas

Nick Holonyak Jr. had just returned from Tokyo, where he received the $500,000 Japan Prize for his role in the microelectronics revolution. But the pomp of the ceremony was far from his mind when *Science* visited his office at the University of Illinois, Urbana-Champaign, earlier this month. Instead, Holonyak, a professor of electrical and computer engineering, couldn't stop thinking about the high-brightness light-emitting diodes (LEDs) he saw in place of conventional bulbs on Japanese traffic signs. "The incandescent lamp is doomed," he said gleefully.



Practical man. Optoelectronics innovator Nick Holonyak Jr.

If LEDs do turn the lightbulb into a museum piece, it will be yet another technological sea change flowing from Holonyak's work. The Japan Prize—that country's equivalent of the Nobel Prize—went to Holonyak for a long line of semiconductor advances that began in 1962 with the first practical light-emitting diode (LED) for visible light and continues with his group's effort to develop light-carrying "wires" for optical chips (see main text). One factor in those accomplishments is what Holonyak calls his delight in making advances that benefit "the working man." Another, says Jerry Woodall, a professor of microelectronics at Purdue University, is an efficient strategy for transferring his ideas to industry. "He trained the students that went into industry and made [his ideas] commercially viable. I give him a lot of kudos for that."

Holonyak picked up some of his technological optimism in 1951, he recalls, when materials researcher John Bardeen set up shop at the University of Illinois. Bardeen brought with him a small plastic box with keys on one side—a primitive electric piano. The vacuum tube–based electronics of the day needed to warm up before playing, but, says Holonyak, "I was stunned when he turned it on and it played immediately." Bardeen's musical box was one of the first portable devices to use transistors, and that homespun demonstration helped convert Holonyak to the new technology.

Later, when Holonyak moved from transistors to LEDs, he pioneered the use of "alloy compound semiconductors"—substances like gallium arsenide phosphide that are the stuff of today's visible light–emitting solid-state devices. Since then, Holonyak and his students have discovered new ways to formulate and manipulate compound semiconductors, and in 1978 they were the first to achieve continuous operation of a quantum-well laser at room temperature. "He has made an enormous impact," says Woodall.

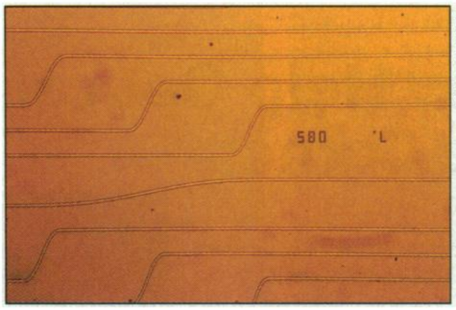
Now, two of Holonyak's former students, George Craford and Fred Kish, are working at Hewlett Packard in San Jose, California, to develop the high-brightness LEDs that Holonyak thinks will someday light offices and homes more efficiently than incandescent bulbs. The revolution will happen "whether anyone wants to believe it or not," says Holonyak, brushing past objections as if he were speaking to devotees of the vacuum tube.

–J.G.

readily emit or absorb light when electrons excited into a higher energy band recombine with positively charged "holes" in the resting energy band. That's why these semiconductors can be made into light-emitting diodes, semiconductor lasers, and light detectors. But light can't be channeled from one device to another on the same chip without some confining mechanism, and that's where the waveguides come in.

One way to create waveguides is to place masks over the crystal and expose it to a plasma, etching deep canyons into the unmasked regions. The canyon walls, like the edges of polished sheets of glass, act as mirrors when photons strike them at glancing angles, trapping light within the "plateaus" on either side. But Larry Coldren, head of the Optoelectronics Technology Center at the University of California, Santa Barbara, notes that "it's difficult to get the sidewalls very smooth." As a result, says Krames, "scattering losses [of the light] can start to kill you." What's more, the etching process can disturb the entire QWH, making it difficult to etch high-quality waveguides on the same chip with light-emitting or detecting devices.

Krames and his colleagues, however, knew of another way to alter the optical properties of aluminum-gallium-arsenide: converting it to a hard, durable oxide material discovered by Holonyak and John Dallesasse in 1990. This oxide has a much



KRAMES ET AL.

Map of the future? Oxide waveguides thread a gallium arsenide–based chip.

lower refractive index than the original semiconductor, and the researchers reasoned that light would be confined to the unaltered semiconductor between oxide regions. To create the oxide waveguides, the group first masked the crystals, then heated them in a humid atmosphere. In the areas left bare by the mask, oxygen from the water vapor reacted with the aluminum, producing a "deep oxide" layer that grew into the crystal.

One challenge awaited the researchers at the center of the QWH, where the lack of aluminum held up the reaction. To get around this problem, the researchers had to smear out the QWH's layers, jumbling aluminum atoms into the center of the well, by diffusing silicon through the structure. Once that hurdle was overcome, the researchers succeeded in producing deep regions of low refractive index, in a process far gentler than etching.

The waveguides bounded by the oxide regions also turned out to leak far less light than etched structures "that you can actually make [an optoelectronic] device out of," says DeTemple, in part because of the lower scattering losses. When the researchers tested the waveguides' ability to carry light around bends, he says, they measured losses an order of magnitude lower than seen in earlier waveguides in QWHs. "The curves are as short as you're going to see" in an optoelectronic circuit, says DeTemple. "It looks wonderful."

Still, even DeTemple cautions that promising advances in this field have had a way of fizzling out. Next, the researchers plan to see whether the waveguides work as well when incorporated into integrated circuits. The group will also have to move beyond the shorter wavelengths studied so far to the infrared light used in telecommunications.

But Krames, DeTemple, and the rest of their group have a powerful spur to their efforts: other researchers' fervent hopes that they will succeed. "For me, this business of turning a corner is absolutely essential," says Harry Jordan, a researcher in optical computing at the University of Colorado, Boulder. "If somebody can figure out how to do that," he says, "I can design the chip."

–James Glanz

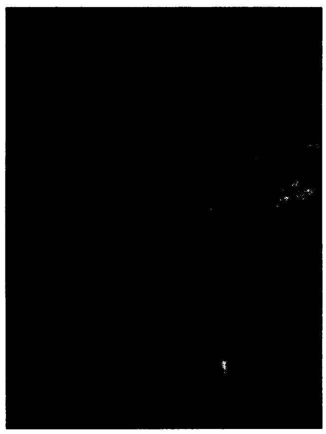
ARCHAEOLOGY

Masters and Slaves in an Iron Age Cave?

PARIS—Death is often described as the great equalizer—but the same can't be said of burial. The rich spend eternity in cushy mausoleums, while the poor elbow each other for space in common graves. And that social distinction isn't new. Nearly 2800 years ago in southern France, 22 people apparently received radically unequal treatment in death, which could help archaeologists understand the origins of social stratification and urban development in this region.

Early this year, explorers and scientists discovered two groups of almost perfectly preserved human skeletons in a cave near the village of Boussac, in the department of Lot. Nineteen of them had gone unadorned to their burials. But three others, apparently interred at the same time in a nearby chamber, were outfitted with jewelry, tools, and weapons.

Such "sharp status differences ... could be really interesting," says University of Minnesota archaeologist Peter Wells, possibly indicating that the 19 unadorned bodies were servants or slaves of the other three more "aristocratic" individuals. Almost nothing is known about the structure of the societies that existed during this period—the early Iron Age—in the Western Mediterranean area. And that makes the cave extremely important, says Michel Vidal, the French archaeology service's conservator for the Midi-Pyrenées region and leader of the research team. So



PHOTOS BY FRENCH MINISTRY OF CULTURE

Aristocratic afterlife? Some skeletons from an Iron Age cave in France had an unadorned burial *(above)*, while others were outfitted for eternity with jewelry and tools *(right)*.

important that, although it was discovered in February, the French government kept the cave's existence secret until late April, when the site could be properly secured.

Vidal says that the details of the implements found with the smaller group of skeletons—an iron lance and knife, iron bracelets, and a bronze torque (neck ring)—are typical of the 7th or early 8th century B.C. This would correspond to the early Iron Age societies in temperate Europe known collectively as the Halstatt culture (named for an archaeological site in central Austria), which flourished from the 8th century to the 5th century B.C. The Halstatt connection makes the Boussac discovery "very particular," says Vidal, because cave burials are extremely rare during the Halstatt period. Wells agrees that "cave burials are very un-