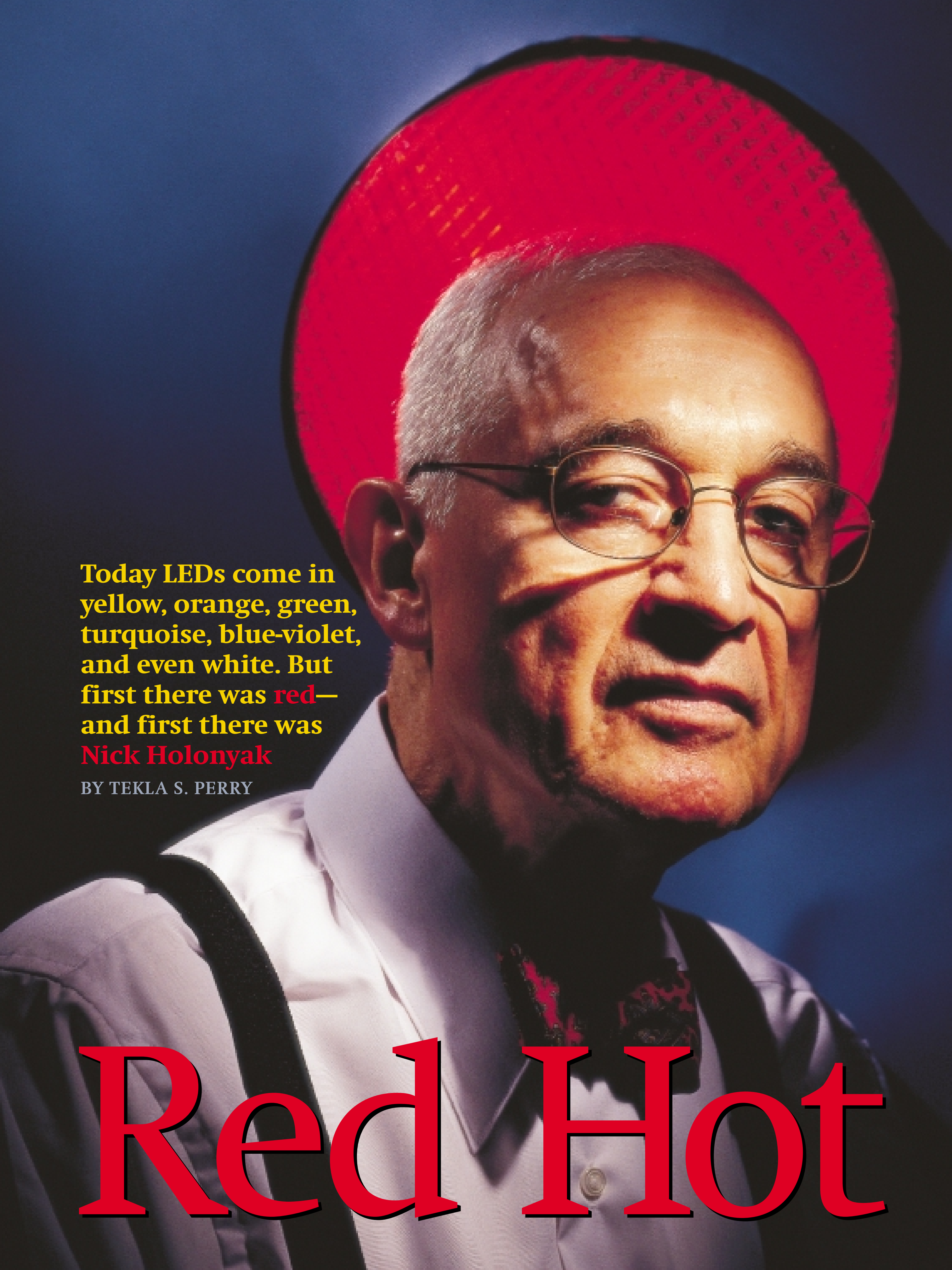

Red Hot

Today LEDs come in yellow, orange, green, turquoise, blue-violet, and even white. But first there was red—and first there was Nick Holonyak

BY TEKLA S. PERRY

THEY SHINE FROM CLOCKS AND TRAFFIC LIGHTS; they blink on our car dashboards. They flash on the soles of children's running shoes; they glow from the coffeemakers in our kitchens. They tell us that our modems are connecting to our networks; they reassure us that our cellphones are on. They lit up the face of the first personal computer and the first wristwatch with an electronic display; they illuminate today's suspension bridges and video billboards.

These tiny semiconductor sandwiches known as light-emitting diodes (LEDs) can now create every color of the rainbow and more. But LEDs all trace their genealogies back to the first visible laser diode—and it was red. The father of that primordial visible diode is Nick Holonyak Jr., the winner of this year's IEEE Medal of Honor.

Summer of '62

It all started in the summer of 1962, when a rock group called The Beatles was signing its first record contract and an astronaut named John Glenn was basking in the glory of his orbital spaceflight. Holonyak, who is now the John Bardeen Endowed Chair Professor of Electrical and Computer Engineering and Physics at the University of Illinois at Urbana-Champaign, was a 34-year-old consulting scientist at General Electric Co.'s laboratory in Syracuse, N.Y. He was fashioning simple devices of germanium and silicon, and investigating the family of so-called III-V materials, such as the semiconductor gallium arsenide.

That July, Holonyak attended the Solid State Device Research Conference in Durham, N.H. Researchers from the Massachusetts Institute of Technology's Lincoln Laboratory (Lexington, Mass.) and RCA Laboratories (Princeton, N.J.) reported there that a device based on a junction between two forms of gallium arsenide could emit photons of infrared light efficiently. This junction brought together two forms of the semiconductor, known as n-type and p-type. In the n-type region, electrons outnumber electron deficiencies, called holes; in the p-type region, the reverse is true. When single crystals of the two types are placed in direct contact with each other, a junction forms at their boundary that permits electrons and holes driven by a current to intermix and emit photons.

Holonyak and some colleagues immediately thought a step further. He explains: "We were saying, 'Wow, what will it take to make this thing coherent?' In other words, what will it take to make this into a laser?"

Holonyak went back to his General Electric lab and began to work exclusively on this question, with the aid of one full-time technician and some additional part-time help. This group was not the only one taking on the challenge. Teams led by Robert Hall, who worked in another division of GE, the Corporate Research and Development Center (Schenectady, N.Y.); Marshall Nathan at IBM Research Laboratories (now the Thomas J. Watson Research Center), Yorktown Heights, N.Y.; and Robert Rediker at MIT's Lincoln Laboratory were also, as were others in the United States and Europe. The race was on.

Hall, Nathan, and Rediker had an early lead because they were working with off-the-shelf gallium arsenide; Holonyak was instead working with an alloy of gallium arsenide phosphide, which he had to make himself. The advantage of gallium arsenide phosphide was its larger band gap, which meant that when electrons and holes combined in the material, they would emit photons of higher energy.

That higher energy translated into higher-frequency photons. Holonyak would get red light rather than infrared light, so he would see his success as a burst of scarlet. A laser made of gallium arsenide, by contrast, would emit infrared light, which could be viewed only indirectly, for example, on photographic film.

But wasn't visible-light emission a small payback for the steep price of having to make the material himself? "Working that way made sense to me," Holonyak responds. Growing up poor in the small rural town of Zeigler, Ill., he "didn't have much of anything," he adds. His father was a Carpatho-Rusyn coal miner who came to the United States in the early 1900s from the mountainous region that straddles the borders of Poland, Slovakia, Hungary, and Ukraine. As a boy, Nick had a pocketknife and liked whittling. "I realized you can make what you want," he states. The lesson stuck, and he applied it to semiconductors decades later. His colleagues thought he was crazy.

For one thing, the method he was using to grow crystals was unconventional. He cooked gallium arsenide and gallium phosphide together with a metal halide in a closed ampoule to create a mixed crystal. "People told me that had I been a chemist instead of an EE, I would have known that growing a crystal this way was impossible," he says. "No one in their right mind would have tried it."

The accepted method would have been to heat a gallium arsenide crystal in a gas of phosphorus so that the phosphorus would slowly displace the arsenic. "It would have taken billions of years to work," Holonyak jokes. "You had to move the atoms and reassemble them in some chemical way."

Holonyak quietly went ahead with his chosen method, because he secretly knew it would work—he had successfully grown gallium arsenide phosphide in an ampoule two years earlier in an attempt to make another kind of device, called a tunnel diode, out of the material. Meanwhile, everyone else was sure that he was in over his head. "They thought I was drowning without realizing it, because no one at that time had ever made anything out of an alloy. There was no alloy device. Not any."

"I thought I would kick those guys' asses and beat them all," he says with a grin.

PHOTOGRAPHS: JEFF SCIORTINO

Hall got to the finish line first—by mid-September 1962 he had demonstrated an infrared semiconductor laser. Holonyak had fallen behind. He was cleaving his crystals mechanically to create the cavities in which the photons had to gather, resonate, and be emitted as light. The method wasn't working because he was having trouble orienting the faces of the crystal correctly, so that they would be parallel.

He was more successful when he followed the suggestion of Hall's boss to switch to polishing the cavities, which is what Hall had done. "I polished up some of my diodes on October 9th," Holonyak says, "and the next day we were looking at red lasers." Holonyak's other two competitors also had working laser diodes by mid-October.

Because Holonyak, unlike his competitors, was working with visible light, he discovered an interesting phenomenon. When he added the phosphorus to the gallium arsenide, the band gap—or the amount of energy it takes to move an electron from the valence band to the conduction band—increased. This reduced the wavelength of the emitted light from the infrared to the red.

As he added more phosphorus, however, the efficiency of the photon production dropped, and "lasing"—in which enough photons are emitted and bounce around within the crystal cavity to trigger the emission of yet more photons that escape as a beam of light—stopped. But sufficient photons were generated to light up the crystal internally, and, because of its short wavelength, this light turned out to be very visible. Since the light wasn't coherent, what he had was a light-emitting diode, not a laser diode. When he added even more phosphorus, "it'd get totally inefficient, and I'd lose the whole thing," Holonyak says.

Besides producing the first LED, Holonyak had also demonstrated that an alloy could be used to make a reliable semiconductor device—a discovery that led to today's heterostructure devices, such as the red lasers used in DVD players, the high-frequency circuits used in cellphones, and more efficient solar cells.

GE quickly rushed these LEDs and visible lasers to market, easily employing a manufacturing line that was packing silicon rectifiers into glass packages by dropping LED chips into the packages instead. The company's price list for December 1962 quotes US $2600 for one of Holonyak's lasers and $260 for one of his LEDs, which were initially used as indicators, replacing meters and nixie tubes in electronics gear.

Today gallium arsenide phosphide LEDs are still on the market and are priced at about 4 cents each. GaAsP lasers were initially impractical, and were employed mainly for experiments; though closely related to today's red lasers, they are no longer used. Because the LED was an old idea that had merely been hard to render in practical form, it was not patentable.

Nick Holonyak Jr.

Present job: The John Bardeen Endowed Chair Professor of Electrical and Computer Engineering and Physics at the University of Illinois at Urbana-Champaign

First jobs: Golf caddy; Illinois Central track repair crew

Family: Married to Katherine for 47 years

Patents: 31 granted, 2 more under review

Hero: John Bardeen

Last books read: *True Genius: The Life and Science of John Bardeen*, by Lillian Hoddeson; *Benjamin Franklin* by Edmund S. Morgan

Favorite restaurant: Tony's Restaurant in St. Louis

Sport: Gymnastics

Car: 1997 BMW M3

Languages spoken: English, Carpatho-Rusyn

From spark coils to dimmer switches

Though no one could foresee how far his talent would take him, it was clear by the time Holonyak entered college in 1946 that his career would involve tinkering with electrical devices. He was fascinated by the spark coils of his godfather's Model T Ford, for instance, and built scavenged electronic parts into telephones.

Because electronic research in those days revolved around vacuum tubes, Holonyak, as a graduate student at the University of Illinois in the early 1950s, became part of a group that was building microwave tubes. Word had spread about the fabulous new device called the transistor, invented at Bell Telephone Laboratories, but Holonyak had never actually seen one.

Then, in 1951, serendipity intervened. John Bardeen, one of the three inventors of that transistor, relocated to the university from Bell Labs. Bardeen was assembling a research group, and Holonyak got permission to leave the microwave laboratory and move into this new transistor laboratory, where he worked on germanium p-n junctions, measuring their leakage effects.

"It was the strangeness of it, the newness of it, that made me want to move," Holonyak says. "I wanted to see what was there."

After graduation in 1954, Holonyak accepted a job as a member of the technical staff at Bell Labs, where his group successfully made silicon p-n junctions and various kinds of transistors and fabricated the first silicon-controlled rectifiers—or thyristors.

After a brief stint with the U.S. Army, during which he was stationed at Fort Monmouth, N.J., and Yokohama, Japan, performing work that is still classified, Holonyak in 1957 joined GE and continued to experiment with silicon thyristors. By the spring of 1958, he was wrestling with this question: why couldn't the thyristors switch when the polarity of the alternating current was negative as well as when it was positive, and therefore avoid wasting half of each power cycle?

He came up with a five-layer thyristor that he knew would work, even though those devices had so far leaked too much energy. He and another researcher, Dick Aldrich, had an idea. They deposited an oxide on both surfaces of a piece of silicon, laid stripes of wax threads on each side, in opposite orientations, to act as a mask, then etched off the oxide in the unmasked areas. The crosshatching meant that when the silicon was processed into a thyristor, a short circuit was created on the top and bottom surfaces, but not internally, where lateral currents could "trigger" the junctions.

Even though the first device so constructed was crude, it easily passed its first test, switching perfectly in both polarities. It came to be known as the triode AC switch, or TRIAC, also yielded a method for making more stable thyristors, and went on to become the heart of dimmer switches for lights.

Holonyak left GE in 1963, heeding John Bardeen's call to join him at the University of Illinois. There, he moved on to work on quantum wells and quantum-well lasers. His patents for processing techniques for quantum wells, used today in making laser diodes, have earned the University of Illinois many millions of dollars. These days, he is investigating methods for manufacturing quantum dot lasers; these would have a sharper output than current lasers and be less sensitive to temperature. This work may turn out to be key in getting optical-fiber lines directly to homes because today's semiconductor lasers don't do well in hot weather, requiring, in some cases, temperature monitors and cooling systems.

But probably the most important thing Holonyak's lab has produced is top EEs. Working with just a handful of students at a time, Holonyak has personally advised some 60 Ph.D. graduates; with those graduates educating others, his influence permeates the industry today.

A big tree

Many of the advances in LED technology have been made by former students of Holonyak's, such as M. George Craford, who developed the first yellow LED back in 1970 and now leads a company called Lumileds Lighting LLC (San Jose, Calif.).

"I first met Nick when I was a graduate student in physics," Craford says. "Taking a tour of his laboratory, I saw him stick an LED into a dewar of liquid nitrogen and suddenly there was a bright light. That fascinated me." Craford ended up switching fields—and thesis advisors.

Holonyak had a similar effect on Russell Dupuis, now a professor of electrical and computer engineering at the University of Texas at Austin. "I took a class on quantum electronics from him when I was a senior," he says. "He is so excited about it that he gets you excited, and I decided right then that I wanted to do what he was doing." Dupuis talked himself into a summer job in Holonyak's lab and continued there through his Ph.D. research.

Dupuis describes Holonyak as one of the "big trees" in the forest, with roots that trace back to John Bardeen, and with a host of branches that are bearing fruit. And the fruit has not just been in LED developments. Dupuis, while at Rockwell International (then in Los Angeles), went on to make the first lasers out of crystals grown by metal-organic chemical vapor deposition (MOCVD).

Don Scifres, another of Holonyak's former students, went on to develop a production version of MOCVD lasers at SDL Inc., a company he founded (now part of JDS Uniphase Corp. in San Jose, Calif.). These lasers are the heart of today's optical communications networks. The list goes on.

Says Dupuis, "There are an incredible number of fruits on Nick's tree that are important to different parts of our lives today."

Attempts to make LEDs out of different materials led to new colors and improved efficiencies, but the principle demonstrated by Holonyak, of using an alloy compound semiconductor to emit light, remained constant.

Today, a major focus of the industry is on getting LEDs to emit white light efficiently, as predicted by Holonyak in 1963, when *Reader's Digest* quoted him: "We believe there is a strong possibility of developing the laser as a practical white source." The writer, Harland Manchester, went on to state: "If these plans work out, the lamp of the future may be a piece of metal the size of a pencil point, which will be practically indestructible, will never burn out, and will convert at least 10 times as much current into light as does today's bulb."

High-brightness LEDs (of all colors) are now a $1.8 billion-a-year U.S. market (making up perhaps half of the overall LED market), according to Robert Steele, director, optoelectronic practice, for Strategies Unlimited (Mountain View, Calif.), a market research firm. Steele expects that in about three years, white LEDs will be practical for use as headlights in cars.

Holonyak is awed at how far LEDs have come since their birth 41 years ago in his GE laboratory. "But being at the front end is a fun time and a fun place," he says simply.

The business of making light emitters, Holonyak says, has not ended, however, "though it is so far along that it's already changing people's lives." ●

To Probe Further

More information on the 2003 IEEE Medal of Honor and this year's other major IEEE medals is available at http://www.ieee.org/portal/index.jsp?pageID=corp_level1&path=newsinfo&file=honors2003dec.xml&xsl=generic.xsl.

Russell Dupuis details the race to invent the diode laser in the February 2003 issue of the IEEE LEOS newsletter, http://www.ieee.org/organizations/pubs/newsletters/leos/feb03/diode.html.

M. George Craford's invention of the yellow LED and Nick Holonyak's influence on his career are described in *IEEE Spectrum*, February 1995, pp. 52–55.