The Breakthrough Birth of the Diode Laser

Jeff Hecht

The most surprising thing about the birth of the diode laser 45 years ago is that it happened so quickly. Physicists had known about light-emitting semiconductors for decades, but the devices drew little attention due to their weak output. Then, a key experiment showed that diode junctions could emit very efficiently, and, within four months, four groups had crossed the threshold to demonstrate diode lasers.

he first step on the road to the semiconductor laser came a century ago in 1907, when a young British engineer working for the Marconi Company in New York unwittingly stumbled upon light emission from semiconductor junctions. Crystal detectors for radio waves had recently been invented, and Henry J. Round was studying what he called the "unsymmetrical passage of current through a contact of carborundum and other substances." The negative poles of a couple of samples glowed with yellow light when he applied 10 volts, and many more glowed when he applied 110 volts.

Round's device was the first light-emitting diode (LED), although he didn't understand its operation. Carborundum is a semiconductor, silicon carbide, and its junction with a metal conductor formed a Schottky diode. Applying a strong forward bias caused electrons and holes to recombine at the junction, releasing excess energy as light. In the 1920s, Oleg Losev in the Soviet Union independently rediscovered the effect and studied it in more detail. He also observed emission from zinc oxide. Yet the feeble emission from SiC and II-VI semiconductors attracted little attention from optical physicists, even after the invention of the transistor launched the semiconductor era.

Gallium arsenide proved to be a much better light emitter, but it wasn't studied until the semiconductor boom of the early 1950s. Its initial attraction was a high electron mobility that looked promising for fast electronic devices.

In 1955, Rubin Braunstein was the first to observe emission from gallium arsenide and two other III-V compounds—indium phosphide and gallium antimonide—at RCA Laboratories in Princeton, N.J. His LEDs were Schottky diodes formed by point contacts or silver paint; junction diodes were not available. He worked at liquid nitrogen temperature, where much less of the recombination energy is lost to nonradiative processes than at room temperature, and observed peak emission close to the band gaps of the compounds, confirming that the light was recombination radiation. His LEDs emitted enough infrared light to play music from a phonograph record, but the light wasn't visible, and scientists' interest in GaAs remained mainly focused on fast electronic devices.

Robert Hall preparing a diode laser for operation (1962).

Laser stimulates emission of new ideas

The idea of the laser renewed interest in light-emitting semiconductors. Theorist John von Neumann drafted a paper on stimulated emission from semiconductors in 1953 but never published it. (It was later included in the June 1987 issue of the *IEEE Journal of Quantum Electronics.*) Charles Townes' successful demonstration of the microwave maser the following year stimulated widespread interest in developing both new maser materials and extending stimulated emission to shorter wavelengths. Pierre Aigrain of the École Normale Supérieure in France and Nikolai Basov of the Lebedev Physics Institute in Moscow separately suggested that population inversions should be possible in semiconductors, but did not focus on junctions.

In 1961, the year after Theodore Maiman operated the first laser, Maurice Bernard and Georges Duraffourg of CNET (the French National Center for Telecommunications Research) proposed that recombination of electrons and holes at a junction could generate stimulated emission at cryogenic temperatures. They suggested direct transitions in a pair of III-V semiconductors, indium arsenide and indium antimonide. However, they erred in thinking that a laser might work on indirect transitions of doped silicon or germanium. They also missed the need for a resonant cavity to sustain laser oscillation. Yet a major problem remained: No one knew how to efficiently generate light from p-n junctions.

A critical experiment

The promise of high-speed electronics had focused attention on GaAs. Robert Rediker began studying it at the MIT Lincoln Laboratory in 1958. He initially made diodes by diffusing zinc impurities into GaAs, then teamed with Ted Quist to make alloy diodes. When they realized that the two types of diodes had quite different electrical properties, Rediker decided to look at recombination radiation from diodes cooled to liquid nitrogen temperature, where nonradiative effects would drain away much less energy than at room temperature.

They enlisted the help of Bob Keyes, who put an alloyed diode into his prism spectrometer, and measured the weak infrared emission that Rediker and Quist had expected. Then they put in the diffusely doped diode. The light completely overwhelmed the instrument. Keyes had to stop down the spectrometer slit and change the chart recorder scale by a factor of 1,000 to record data.

Keyes first calculated the efficiency as 125 percent—a statistic that astounded the Lincoln group. They knew it couldn't be more than 100 percent, but it was clearly the most efficient LED ever seen, and it was also impressively powerful.

To show how robust it was, they modulated its light emission with video signals and transmitted the light through the air. They started by sending the signal 84 m on the lab's roof. Later, they transmitted signals to the lab from the top of Mount Wachusett, 50 km to the west, an impressive achievement that required clear weather and a very sensitive receiver, but excited the military sponsors of the Lincoln program.

Keyes announced their results on July 9, 1962, at the Solid State Device Research Conference in Durham, N.H. Afterwards, Hank Summers of RCA stood up to say that the light generation they reported was so high that it violated the laws of thermodynamics. In reply, Keyes deadpanned, "I'm sorry."

Once the audience stopped laughing, Robert Hall of the General Electric Research Laboratory in Schenectady explained that the Lincoln experiment had not really violated the conservation of energy. Separate experiments reported at the conference by Jacques Pankove of RCA confirmed that GaAs junctions could emit light very efficiently. Later measurements at Lincoln showed the actual efficiency was 85 percent.

The Lincoln experiment was a breakthrough in light emitting semiconductors, reported in the *New York Times*. It marked both the highest power and the highest efficiency ever recorded from an LED, albeit one emitting in the near infrared.

Thinking on the train

The implications of the Lincoln experiment were obvious to Hall as he rode the train back to Schenectady. An expert in semiconductor fabrication, he had heard about diode lasers before. He hadn't been impressed by earlier proposals because they required highly reflective mirrors and long optical paths to compensate for low-efficiency light emission. The high efficiency of the Lincoln diodes changed that.

Hall made rough calculations on the train. "It looked as though you could get a population, and then the thing ought to work, if you could build the right kind of structure," he recalled. Having learned optics during his high-school days as an amateur telescope maker, he decided to make an optical cavity by polishing the edges of the semiconductor chip.

Back at GE, Hall spent a few days working out details. He recognized that the diodes would have to be doped heavily, so the active layer would be only about a micrometer thick. That meant that the resonant cavity needed to be along the junction plane to accumulate reasonable gain. He wasn't sure his idea would work. "It was something of a long shot, with the chance

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of success being around one in five, but even if we never produced any coherent light, we were bound to learn a good deal about the high-efficiency junction luminescence."

Keyes's talk had put the diode-laser idea in play, so Hall quickly gathered a team and got management approval. He planned to try his simple design, and then use the results of his first experiments to refine his approach. He fully expected problems, because no one knew how much gain to expect in the junction plane, or how to best test for laser action. They had to make the diodes, fire electrical pulses into them while immersed in liquid nitrogen, and then measure the infrared output.

After about a month, they had diodes ready for Gunther Fenner to begin testing. A few emitted reasonably, but some were dead

shorts and others simply disintegrated under the high current. Results improved when he shorted the drive pulses from milliseconds to 5 to 20 $\mu s.$

Two months into the project, on the morning of Sunday, September 16, 1962, emission from diode L-52 increased rapidly when Fenner cranked drive current above 12 amperes. An infrared viewer showed him a bright horizontal line that clearly wasn't spontaneous emission. That was exciting enough to call in Hall's boss, Roy Apker, to have a look on the weekend. Nobody ever figured out what produced the line, but Monday morning's results were even better. When the drive current passed a threshold, the spectrum changed drastically and interference patterns and modes appeared, as expected for a laser as thick as the junction.

Weeks of frantic activity followed as the GE team gathered more data, refined measurements, and wrote up patent applications. In the midst of it all, Maurice Bernard dropped by the Schenectady lab for a regular visit. But Hall couldn't say anything about the diode laser he had operating in the next room. *Physical Review Letters* received Hall's paper on September 24, 1962, a mere 77 days after Keyes's paper. The article, which appeared in the November issue, was a scientific tour de force—but it wasn't alone.

A parallel success at IBM

Nobody from the IBM Watson Research Center in Yorktown Heights, N.Y., had attended the New Hampshire meeting. However, the *New York Times* report of Rediker's bright emission caught the eye of Rolf Landauer, a department head who had been trying to launch a diode-laser program for more than a year.

At that time, IBM was working on high-speed GaAs transistors, and Peter Sorokin's early success with four-level solid-state lasers had made lasers a hot topic at IBM. But Marshall Nathan had not taken the idea of making a diode laser very seriously



Courtesy of GE

until Landauer told IBM's semiconductor group about the Lincoln diodes. Nathan wasn't sure he should believe the near-100-percent efficiency, but it gave credence to other reports of efficient electroluminescence from GaAs.

Landauer asked Dick Rutz to make some GaAs diodes. Nathan measured their 840-nm emission and initially found their efficiency was only about 10 percent. That didn't discourage Landauer. Nor did IBM's struggle with designing a resonant cavity for diodes. Sorokin, Rutz and Rick Dill tried to use the GaAs emission to pump one of Sorokin's four-level lasers. It would have been the first diode-pumped laser, but they couldn't reach laser threshold.

Nathan and Gordon Lasher then decided not to try making a cavity that selected resonant modes. That left the question of how to demonstrate that they had stimulated emission. Bill Dumke proposed looking for line narrowing—an effect that Ted Maiman had used to show laser action in ruby. Nathan wasn't convinced that it would work. However, as he cranked the power up, linewidth slowly narrowed from 12 nm to 9 nm to 3 nm.

By then it was nearly 6 p.m. on a Friday evening, Nathan recalled. He figured it was important enough to disturb Landauer at home. They had no idea that Hall's paper was already with *Physical Review Letters*, so they tested other diodes, and pushed their original diode to a 0.2 nm linewidth. Then, they dashed off a paper to *Applied Physics Letters*, which was published in November 1962. It was September 28, 1962—four days after Hall's paper had been received at *Physical Review Letters*.

"No attempt was made to obtain highly resonant electromagnetic modes," they wrote, but they calculated that they had produced about 100 photons per mode. In retrospect, Fresnel reflection at the surfaces of the GaAs may have provided enough feedback for stimulated emission to dominate when they pumped 10 amperes through their liquid-nitrogen cooled diode.



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Diversions at Lincoln Lab

Rediker didn't expect other groups to start so quickly on the diode laser. He found himself distracted by the communications experiments. It took a push from Ben Lax to get him going.

Lax had looked at diode laser concepts before with Lincoln theoretician Herb Zeiger. They had been stalled by the lack of good materials until the bright GaAs diode came along. Zeiger, who had worked with Townes on the microwave maser, suggested polishing the edge of a small rectangular GaAs chip to produce laser oscillation along the junction plane, a design similar to Hall's. "We understood exactly what we had to do," Rediker recalled.

The problem was getting it done. The Lincoln group searched in vain for optics companies who knew how to polish GaAs chips. (Quist later suggested that they might have saved time if they had dropped a sample on the floor and realized it could have been cleaved.) In September, they finally began polishing their own GaAs chips to the configuration needed for the laser experiment.

After that, progress was rapid. Late in the afternoon of Friday, October 12, Quist spotted intense filaments showing laser operation when he examined the output of one diode with an infrared viewer. He and Rediker spent Saturday nailing down vital details showing laser operation, and submitted a report received on October 23 by *Applied Physics Letters*. It was good work, the first to show that cooling to liquid helium temperature enhanced laser operation. By then, however, GE and IBM had already won the race. As Rediker wrote later, "We underestimated the competition!"

Seeing red: The first visible diode laser

Nick Holonyak Jr. heard Keyes's talk at the solid state conference, and returned to General Electric's Syracuse laboratory impressed by both the GaAs diode's emission efficiency and its power. But Holonyak took off in his own direction. Instead of using GaAs, he decided to work with gallium arsenide-phosphide, which he had developed in an effort to make better tunnel diodes. Adding phosphorus increased the band gap, so its emission would be visible. He reasoned that being able to see his photons would give him an edge in demonstrating laser action.

Holonyak also envisioned an external-resonator diode laser. In August, he talked with Hall, who said he was polishing the edges of his GaAs lasers to form a cavity. Holonyak recommended cleaving the crystals, but Hall stuck with polishing, and Holonyak ran into trouble cleaving the polycrystalline GaAsP in his diodes. Holonyak was still struggling with cleaving in early October when Apker called from Schenectady to tell him that Hall's laser had worked.

When Apker suggested polishing instead of cleaving, Holonyak couldn't argue with Hall's success. He polished and assembled a batch of GaAsP diodes from a crystal he had grown in September, and on October 10 he drove to Schenectady to test the diodes with Hall's instruments. With low currents of 20 to 100 milliamperes, the diodes emitted visible red light at room temperature. Laser operation required pulsing at much higher currents and cooling with liquid nitrogen. As drive current increased from 11,000 to 19,000 amperes per square centimeter, passing the laser threshold, linewidth narrowed sharply from 12.5 to 1.2 nm, peaking at 710 nm.

Knowing that Hall's paper was in the works at *Physical Review Letters*, Holonyak sent his to *Applied Physics Letters*, which received it on October 17—six days before Rediker's—and published the two in the December issue. "Little did I realize how much publicity would be attached to semiconductor lasers," he later recalled. The *New York Times* was quick to report the papers by Hall and Nathan. Holonyak had the first visible diode laser, but he was out of luck. His paper appeared at the time of a major newspaper strike in New York, and went unnoticed.

Ironically, it was Holonyak's room-temperature red LED that had the most immediate practical impact. $GaAs_{0.6}P_{0.4}$ has

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Courtesy of Nick Holonyak Jr



Courtesy of Nick Holonyak Jr.

a direct bandgap, so it emits brightly and efficiently at 660 nm, and it became the standard material for red LEDs. However, it can't be lattice-matched to make heterojunctions, so it has never been used in practical diode lasers.

Follow-on developments

The first diode lasers were remarkable achievements. Demonstrated a little more than two years after the first laser of any kind, they showed a mastery of both compound semiconductors and laser physics. Yet diode laser performance was also severely constrained, so red LEDs reached a mass market long before any diode-laser product.

The fundamental problems with early diode lasers were their requirements for cryogenic cooling and intense current pulses that caused rapid degradation. The key idea that ultimately overcame that problem was using heterostructures to improve current and light confinement. Herbert Kroemer, then at the Varian Central Research Laboratory in Palo Alto, proposed the concept for lasers in 1963. Zhores Alferov of the A.F. Ioffe Physico-Technical Institute in St. Petersburg [then Leningrad] independently developed the concept in the Soviet Union, and refined it to make low-threshold double-heterostructure lasers. The two shared the 2000 Nobel Prize in physics for their work. After Alferov made the first continuous-wave room-temperature diode lasers, Bell Labs refined the technology and reached operating lifetimes of a million hours.

Both diode lasers and LEDs have come a long way. Hundreds of millions of GaAs-based diode lasers are sold each year for use in CD players, CD-ROM drives, laser printers, laser pointers, and a wide range of other devices. Quaternary InGaAsP lasers, developed at Lincoln by J. Jim Hsieh in the 1970s, transmit signals through the global fiber-optic telecommunications network. Gallium nitride diode lasers emitting blue light, invented by Shuji Nakamura in the 1990s, are emerging onto the mass market in Blu-Ray and HD-DVD optical drives for high-definition video.

Discoveries happen when the right people are in the right place at the right time. The optical pioneers who developed the diode laser benefited from a series of rapid developments in



Close-ups of the first visible diode laser viewed in ambient light 40 years after the original demonstration, along with a piece of the bulk material.

both lasers and semiconductors. They had been friends working in a small field before it took off, and they remained friends afterwards, without the bitter feuds that sometimes follow such rapid advances. It was an enjoyable time, says Quist, looking back. "The best part of it was the people that were involved." \wedge



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