



The Diode Laser

The First 30 Days, 40 Years Ago

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In the space of only a month, history was made four decades ago when four groups of researchers independently developed and demonstrated their own versions of the injection laser. The author describes how the experiments laid the foundation for the vast array of materials and technologies used in the fabrication of modern compound semiconductor alloy devices.

A little over 40 years ago, on Sept. 16, 1962, Gunther Fenner, a member of the team headed by Robert N. Hall at the General Electric Research Development Center in Schenectady, N.Y., operated the first semiconductor diode laser.¹⁻³ Within about 30 days, workers in three other laboratories in the United States had independently demonstrated their own

versions of the injection laser. The efforts of the other three groups that also succeeded in making a semiconductor laser in late 1962¹¹ were led by: Nick Holonyak Jr.⁴⁻⁶ at General Electric's Syracuse, N.Y., facility; Marshall I. Nathan^{7,8} at IBM Research Laboratory, Yorktown Heights, N.Y.; and Robert Rediker^{9,10} at MIT Lincoln Laboratory, Lexington Mass. While three of these early *p-n* junction

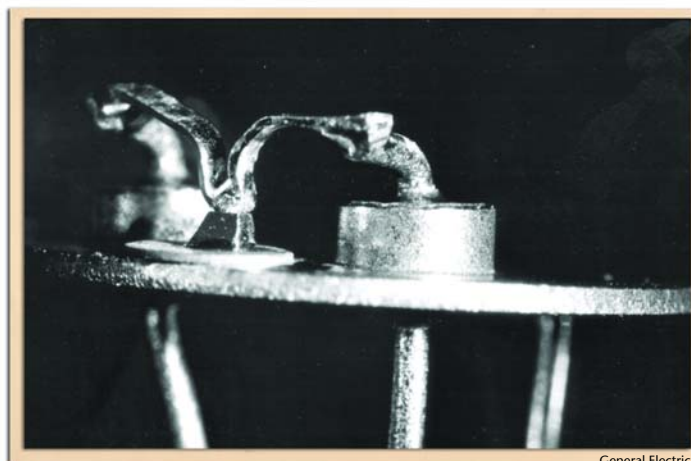
lasers were fabricated by zinc (Zn) diffusion into conventional (and commercially available) *n*-type gallium-arsenide (GaAs) "bulk" crystals, one of the "first" laser diodes (Holonyak's) was created from a small piece of single-crystal ternary gallium-arsenide (GaAsP) alloy material grown by vapor-phase transport, making it the first alloy compound semiconductor device to assume

commercial importance. From this humble beginning, the vast array of materials and technologies used in the fabrication of modern compound semiconductor alloy devices has emerged.

What are GaAs p - n junctions good for?

While germanium (Ge) and silicon (Si) were well-known semiconductors by the late 1950s, the III-V compound semiconductors (sometimes referred to at that time as “intermetallic compounds”), were not well studied and had no obvious unique application. By 1960, Si had become the dominant semiconductor because of its large bandgap relative to Ge and because of the beneficial features of its native oxide, SiO_2 , discovered by Carl Frosch in 1955. It was not clear exactly what benefits could be obtained by replacing Si with GaAs, since GaAs had no stable native oxide and was much more difficult to make in high-purity form. Consequently, as late as 1958, few device researchers considered GaAs worth much effort. Only in 1952, in fact, had GaAs been identified as a semiconductor by Heinrich Welker of Siemens in West Germany.¹²

The search for a higher voltage tunnel diode was one of the motivations behind the study of GaAs diodes. By the early 1960s, heavily doped n -type GaAs substrates—produced by both Czochralski and horizontal Bridgman growth technologies—were commercially available; fabrication of the junction of these devices was in some respects relatively straightforward since the means of forming p - n junctions by use of diffusion and alloying techniques were well known. The form of the p - n junction in the first GaAs laser diodes was relatively conventional, consisting of an n -type GaAs “host” crystal into which Zn atoms were diffused to create a heavily doped p + region. One application of contemporary interest for these diffused and alloy p + $-n$ diodes was the study of tunneling phenomena in heavily doped (degenerately doped) p + $-n$ + diodes. The electric characteristics of GaAs diffused-junction diodes had



General Electric

(Above) The first semiconductor laser was made of GaAs and had a diffused p - n junction. It had polished facets and operated only under pulsed conditions at cryogenic temperatures. (Facing page) The GE Corporate Research Lab semiconductor laser team, led by Bob Hall, examines the cryostat used to test the first diode laser. (Left to right) Jack Kingsley, Dick Carlson, Gunther Fenner, Ted Soltys and Bob Hall.

been under study for some time and their optical properties were beginning to be explored as well. In fact, it was the amazing electroluminescence efficiencies of such diodes that were reported at the Solid State Device Research Conference (SSDRC) on July 9, 1962, by R. J. Keyes and T. M. Quist¹³ of the MIT Lincoln Labs group and by a group led by J. Pankove at RCA Laboratories. These workers reported that their GaAs p - n junctions had extremely high internal quantum efficiencies—as high as 85-100 percent!^{10,14} The Lincoln Labs group also reported using a GaAs diode to demonstrate the optical transmission of television signals from Mount Wachusett to the roof of the Lincoln Labs facility, a distance of about 50 kilometers as the crow flies—quite possibly the first demonstration of the optical transmission of an electronic signal.^{10,15}

While the basic elements of the light-emitting properties of GaAs p - n junctions had been known several years prior to the 1962 report, some of those in attendance at the SSDRC complained that these high-efficiency electroluminescence results violated the second law of

thermodynamics!¹⁰ What made the announcements electrifying was that it suddenly became clear that a semiconductor diode could be a very efficient generator of photons, perhaps the most efficient “converter” of electrical energy into optical energy ever demonstrated.¹⁶ This revelation was an important motivation for some working in the field to pursue their dreams of making a semiconductor laser. The race for the semiconductor injection laser was on.

Of course, Lincoln Labs had a sizable lead in some respects since it already had a relatively large research group experienced in the study of GaAs diodes. Earlier in 1961 and even before, various other groups, including IBM Research Labs, had considered the concept of a semiconductor laser. The IBM group even had a U.S. Army-sponsored research contract to make such a device.^{8,17} Research groups in the United Kingdom had also joined the chase for a semiconductor laser; there were well-organized GaAs p - n junction research activities at the Royal Signals and Radar Establishment under Cyril Hilsum. In the Soviet Union, Nikolay G. Basov and co-workers at the Lebedev Institute in Moscow and D. N. Nasledov and co-workers at the Ioffe Physico-Technical Institute in Leningrad were also considering how to achieve population inversion in a semiconductor.^{18,19} In France, Pierre Aigrain at École Normale Supérieure had proposed that laser operation of a semiconductor could occur; in 1961, he was reportedly planning to visit the United States with a working semiconductor laser in his pocket!²⁰ In 1961, Maurice Bernard and Guillaume Duraffourg, working at CNET in France, had also published a paper analyzing the possibility of laser operation in semiconductors.²¹

How do you make a semiconductor laser?

The concept and demonstration of light amplification by the stimulated emission of radiation, i.e., LASER operation, had

been under active discussion in the late 1950s. The discussion culminated in the demonstration of the solid-state ruby laser on May 16, 1960, by Theodore Maiman, who was working at Hughes Research Labs. By 1962, it was well known that the light from a ruby laser—a visible laser operating in the red spectral region—exhibited several properties unique to coherent radiation, including the characteristic presence of “laser speckle” which could be observed by the human eye when the laser was operated above threshold.^{22, 23} Since the first laser demonstration in 1960 (and even before), some researchers exploring semiconductor diodes had wondered if a semiconductor had the necessary qualities to support stimulated emission and laser operation. Others believed that the possibility might indeed exist.²⁴ John von Neumann had considered the essential elements of a semiconductor laser theoretically in 1953.²⁵

Few parallels with the MASER

Of course, the basic quantum mechanics occurring in a direct-bandgap semiconductor would be fundamentally different from those behind the radiative recombination and laser operation of chromium ions in ruby and the earlier demonstration of the microwave amplification by the emission of radiation (the MASER) using ammonia molecules. There was no clear path for taking what was known about stimulated emission as demonstrated for discrete atomic states—like those found in ruby—and translating it to the broad density of states found in the band structure of a typical semiconductor.

In fact, some of the approaches being explored in 1962 involved indirect semiconductors, e.g., Si and Ge, as well as putting rare-earth atoms into the semiconductor “host” crystal, e.g., uranium (U) or neodymium (Nd), to create “atomic-like” energy transitions (like the Cr⁺ ions in a ruby crystal) within the band structure of the semiconductor crystal (an approach that has not borne fruit to this date).

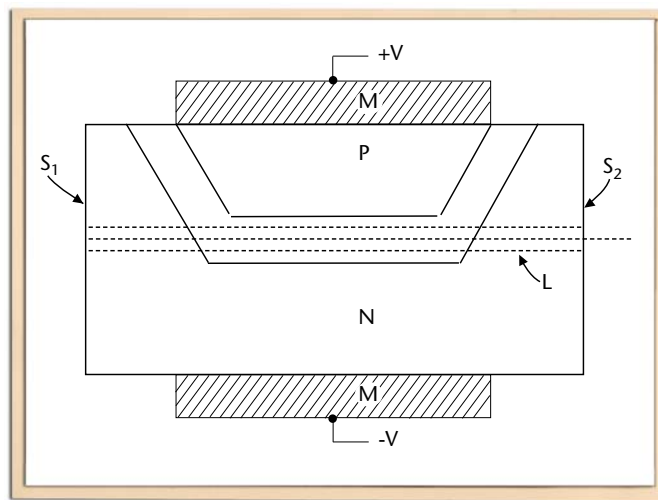


Figure 1. Schematic diagram of initial concepts for an injection laser developed at General Electric Research Laboratories by Robert Hall in 1962. [From R. N. Hall, *IEEE J. Quant. Electron.* QE-23, 674 (1987), Fig. 1.]

A practical problem faced by everyone interested in making a diode laser was how to determine that it was in fact lasing. While it may seem somewhat difficult to understand with the benefit of hindsight, many of those thinking about diode lasers in 1960-62 were not certain as to what to look for to determine the laser “threshold” or that lasing was indeed occurring. Since 1960, it had been obvious that coherent light should produce some type of interference pattern, but such a pattern was not perhaps uniquely created by simultaneous emission originating from a small aperture typical of a GaAs diode. As Robert Hall has written: “It seems strange now, but at that time, one of our big uncertainties was to know what to look for as evidence that the diode was lasing.”³

For Hall, who already had extensive experience with GaAs alloy junctions, tunnel diodes and light-emitting diodes, the attempt to make a laser diode was an extension of his earlier research work. It also coupled with the optics experience he had gained in earlier youthful hobbyist efforts to build telescopes and polish lenses and mirrors.³ Hall’s laser project team included Dick Carlson, Gunther Fenner, Jack Kingsley and Ted Soltys. While other groups thinking about

semiconductor lasers had proposed to use a macroscopic “external cavity” into which a GaAs diode was placed, Hall decided to polish parallel faces onto his GaAs diodes so that the Fabry-Pérot optical cavity geometry was built into the device. This approach was not universally applied and, in fact, the importance of optical feedback into the diode’s “active region” was not fully appreciated by many workers. Hall’s team operated their first successful GaAs laser diodes under pulsed conditions at 77 K on Sept. 16, 1962.¹ A

schematic diagram of Hall’s early concept for an injection laser is shown in Fig. 1. The first verification of laser operation was made through the observation of near- and far-field interference patterns using an infrared (IR) up-converting “snooper scope” which was being used in Hall’s lab to study the emission from such infrared light emitters.

As noted above, IBM had also mounted an early effort to develop a diode laser. In 1961, Rolf Landauer, recently appointed a department director at the relatively new IBM Research Lab at Yorktown Heights, N.Y., had initiated the IBM team effort in the development of a GaAs laser diode.⁸ The IBM team, like Hall’s group and the group at Lincoln Labs, concentrated on Zn-diffused GaAs *p-n* junction diodes, with which they had had previous experience in the development of GaAs bipolar transistors. The team included Rick Dill, William P. Dumke, Bob Keyes (a different person by the same name was on the Lincoln Labs team), Gordon Lasher, John Marinace, Marshall Nathan, Michael Stern and others.⁸ The IBM GaAs laser team was inspired to accelerate its own research effort by the Lincoln Labs’ presentations at the 1962 SSDRC. Although no one from IBM had actually been present, the team had read an article describing the results in the July 10, 1962 edition of *The New York Times*. They had also heard Sumner Mayburg of GTE Sylvania Laboratory speak in a seminar at IBM in January 1962 of his recent observations of high-efficiency radiative recombination

from GaAs p - n junction diodes.²⁶ Landauer, Dumke and Keyes had clearly been thinking about the semiconductor laser problem for some time prior to the June 1962 SSDRC conference; Dumke, in particular, had calculated the requirements for population inversion in a semiconductor.²⁷ The first sentence of Dumke's paper (submitted April 3, 1962), reads: "Since the initial operation of the ruby maser, there has been considerable speculation concerning the possibility of observing maser action in semiconductors such as Ge and Si." After rejecting the possibility of laser operation in the indirect semiconductor Ge due to excessive free-carrier absorption, near the end of this paper, he concluded: "At present, it is not clear whether or not one would obtain anything like typical maser action from a device utilizing direct transitions as in GaAs."²⁷

After hearing the news of the 1962 SSDRC reports on efficient GaAs diodes, the IBM team was spurred to an increased level of activity. Several members of the newly expanded laser team dedicated their efforts to making diodes and analyzing their performance. Gordon Lasher considered what might theoretically be observed in the stimulated emission spectrum of a GaAs diode. Marshall Nathan concentrated on studying the photoluminescence and electroluminescence from various GaAs structures operated under pulsed conditions at low temperatures. While the IBM team realized that for a diode laser, spectral line narrowing should occur and that the light output versus current should be superlinear, because they could not figure out how to provide proper "cavity mirrors" for the diodes, no provision was made in this early work for optical feedback.⁸ On Sept. 29, 1962, Nathan observed narrowing of the electroluminescence to a FWHM of ~ 3 nm. A few days later, he found that the linewidth measured for this first successful diode was the limit of the spectrometer: ~ 0.2 nm. The GaAs diodes showing "stimulated emission" first reported by the IBM group did not employ an optical cavity.^{7,8} The IBM paper describing the group's first stimulated emission results

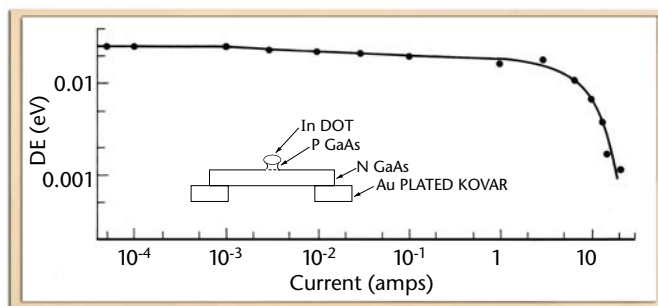


Figure 2. Spectral linewidth vs. current for a GaAs diode made at IBM and operated at 77 K. The diode did not have a Fabry-Pérot geometry so cavity modes were not observed. [From Nathan, IEEE J. Quant. Electron. QE-23, 679 (1987).]

was submitted to *Applied Physics Letters* (received on Oct. 6, 1962) and published on Nov. 1, 1962.⁷ Later, Rick Dill and Dick Rutz developed a process for formation of the optical cavity by cleaving all four sides of the laser diode.²⁸

The early Lincoln Labs GaAs program was quite small; it involved two technical staff members and a technician. The team's work on GaAs was initiated in 1958 to study the possibility of making III-V high-speed microwave devices.^{10,29} The III-V program was driven by the vision of Robert Rediker, who championed the study of GaAs when most other groups were concentrating on silicon. Rediker had visited professor Heinrich Welker in Erlangen, Germany, in 1958 to learn more about GaAs and related materials. While working at Siemens, Welker had been the first person in the West to identify the "intermetallic" III-V materials as semiconductors.

The Lincoln team developed a diffusion technique for producing p - n junctions. The team's laser effort had, in fact, evolved from the work of Rediker's group on the comparison of the electroluminescence characteristics of GaAs diffused and alloy diodes. Keyes was invited to join the team since "he owned the spectrometer."³⁰ As noted above, the work of Keyes and Quist on the study of the recombination radiation from diffused GaAs p - n junctions led to the observation and report of high internal quantum efficiencies, which "sparked" the post-SSDRC efforts at many research labs to develop a semiconductor laser. The

Lincoln Labs semiconductor laser effort presumably benefited in various ways from theoretical papers on semiconductor lasers written by Benjamin Lax, Herb Zeiger and Bill Krag in 1959.^{31,32} As noted, above, Lincoln Labs' work was devoted to the development of efficient emitters and included several

key contributors to the theory and the experimental characterization of the recombination radiation from GaAs p - n junctions. In 1962, this effort—centered in Rediker's group—included Bob Keyes, Bill Krag, Ted Quist, Al McWhorter, Herb Zeiger and others. The search for laser operation from GaAs diodes fabricated at Lincoln Labs met with success on Oct. 12, 1962,³³ with laser operation first confirmed by the observation of "filaments" in the near-field pattern of a GaAs diode when examined with an infrared converter.⁹ The Lincoln Labs device employed a Fabry-Pérot cavity having polished parallel facets, as suggested earlier by Zeiger.³⁴ The paper in which these laser results were described was submitted to the editor of *Applied Physics Letters* on Oct. 23, 1962. It was published (after changes) on Dec. 1, 1962. A photograph of one of the early Lincoln Labs' GaAs laser diodes is shown in Fig. 3.

Do alloys work?

It is interesting to note that in 1960-62, many in the field of semiconductors were convinced that an alloy was not worth pursuing and, that if such materials were to be successfully produced, random alloy "disorder" would render them useless because of the stochastic nature of the distribution of atoms in the lattice.³⁵ There were also different ideas about how to produce such alloys. One, for example, (which has not succeeded even to date) involved the diffusion of P into GaAs to create GaAsP layers. Epitaxial growth of semiconductors was still a very new concept and while the creation of alloyed p - n junctions using metal "performs" was a well-known process, it lacked the control necessary to create true alloy semiconductors.

Holonyak had been working on the growth of ternary GaAsP alloy

materials since 1960. Following John Marinace's 1960 SSDRC report of his work at IBM on the vapor-phase-transport epitaxial growth of Ge on GaAs, Holonyak was interested in using the closed-tube vapor phase epitaxy (VPE) process to create larger bandgap tunnel diodes and p - n junctions and had exploited and extended this materials technology to create $\text{GaAs}_{1-x}\text{P}_x$ crystals and GaAsP layers on GaAs and on other $\text{GaAs}_{1-y}\text{P}_y$ "substrate" materials. This work was essentially the beginning point for all future alloy semiconductor and III-V heterojunction devices. Holonyak, working with the support of a few technicians, developed techniques to grow GaAsP alloy crystals with various As/P ratios, sawed crystals from these small wafers and processed and tested diffused p - n junction devices made from these materials. Holonyak was under pressure from GE management to devote more of his efforts to Si-related work—in fact, his work on GaAsP was largely funded by an Air Force contract managed out of Hanscom Field. On more than one occasion, Holonyak was told that if his external funding stopped, so would his GaAsP project. The implied threat was: "If your external funding ends and you don't want to work on our Si-related projects, you might as well get on the road!"

Holonyak, like Hall and others, was excited by the possibilities described in the Lincoln Labs' paper at the July 1962 SSDRC. Working with GaAsP diodes in his Syracuse lab, Holonyak believed he had an important advantage over others working on the diode laser problem using GaAs—he could see the light coming from his diodes and could therefore also see the near- and far-field patterns. This meant that he could determine quickly whether the diodes were lasing or not by looking at the diode spatial emission characteristics and also by the same well-known "laser speckle" produced by the visible ruby laser.³⁶ At the SSDRC, Holonyak thought about forming an external cavity for the optical feedback. His ideas on cavity formation changed after discussions with Hall. Although Holonyak and Hall had a joint contract with the Air Force for

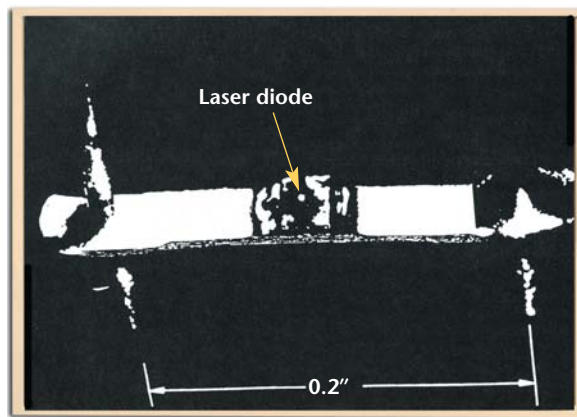


Figure 3. Photograph of an early GaAs diode laser fabricated at Lincoln Laboratory. [From R. H. Rediker, IEEE J. Quant. Electron. QE23, 692 (1987), Fig. 2.]

semi-conductor device research (and, under this funding agreement, shared some ideas), they were geographically separated, still "competitors" and operated essentially independently as far as making the first laser is concerned.^{37,38} After the 1962 SSDRC, Holonyak and Hall did discuss the problem of formation of Fabry-Pérot cavities. They also shared ideas on how to make a laser cavity as early as Aug. 31, 1962.⁵ Hall proposed the use of the semiconductor diode faces as mirrors. His approach was to lap and polish the diode facets. Holonyak decided to try to cleave the Fabry-Pérot mirrors for his optical cavity (an idea apparently initially overlooked by other groups trying to make a laser diode). This approach, although it was later nearly universally used to create diode laser facets, actually delayed Holonyak's first GaAsP laser demonstration because of the difficulty he experienced in identifying the appropriate cleavage planes in his small "bulk" GaAsP crystallites. (The GE lawyers decided not to file for a patent on the idea, but the IBM team did ultimately file on the concept.)

Sometime after the successful operation of the first semiconductor lasers at GE's Schenectady lab, Roy Apker, Hall's boss, called Holonyak at Syracuse to tell him that Hall's group was running a diode laser and suggested Holonyak should stop trying to cleave facets.

Holonyak decided to polish facets and quickly developed his own "home-made" process to do just that. On the first try, on Oct. 9, the process was successful in producing a "good" set of diodes that was tested on Oct. 19, 1962; the diode testing apparatus at Hall's Schenectady lab was used since it was better equipped for this study.³⁵ The first of Holonyak's GaAsP diodes to be tested operated as lasers under pulsed conditions at 77 K. But Holonyak,

believing the game was over since Hall had beaten him to a laser, did not think it urgent to write up his results. Consequently, it was days later in October that he finally got around to writing up the GaAsP laser results and to submitting them to a new journal, *Applied Physics Letters*.⁴ These results (received at *Applied Physics Letters* Oct. 17, 1962) demonstrated a compact and efficient source of visible coherent light and would ultimately be the basis of the first commercially available visible semiconductor light emitters. They would also be the genesis of the now ubiquitous "light-emitting diode" (LED), which is almost universally understood to imply a device that creates photons "visible to the human eye" based upon minority carrier injection and radiative recombination of excess carriers. The demonstration of an *alloy semiconductor laser* at essentially the same time as the GaAs laser provided dramatic and ample proof that alloys were good for something after all. Sometime after the first demonstration of the GaAsP laser, Holonyak arranged for a photograph to be taken of the emission from one of his diodes. Reproduced in Fig. 4, it was the first photograph of a diode laser made from its own light.

Who wants to buy lasers or LEDs?

On Nov. 28, 1962, not long after the first laser demonstrations, GE held a semiconductor laser conference at Schenectady for representatives of the Department of Defense. Some in GE had already recognized that this very "disruptive" technology could have important defense and commercial applications. Before the end of 1962, GE offered both GaAs and

GaAsP lasers for sale, becoming the first company to offer such devices commercially.³⁹ Since the devices only operated pulsed at low temperatures, they were obviously useful only for research purposes or special defense applications. The price for one of Hall's IR-emitting GaAs laser diodes was initially \$1,600—a price which had been somewhat arbitrarily set by the GE marketing group at 10 times that of a currently available Texas Instruments IR incoherent "LED." The price was later reduced to \$800.³⁹ The "visible red" GaAsP laser diode was initially priced at \$3,200, then reduced to \$1,600.³⁹ This pricing decision was based on the fact that GE's marketing managers decided that Holonyak's visible laser was "twice as valuable" as Hall's IR-emitting laser device. Incoherent GaAsP visible LEDs were also offered for sale. Interestingly, 40 years later, GaAsP red-emitting LEDs are still sold. While some researchers did not appreciate the fundamental distinction between "infrared" GaAs lasers and "visible" GaAsP lasers, Holonyak was acutely aware of the significance of visible-spectrum LEDs and lasers, a feeling shared by others working in the field.⁴⁰ These first visible injection lasers made of the ternary alloy GaAsP foreshadowed the future when virtually all semiconductor lasers would employ alloy materials. In addition, the GaAsP first compound semiconductor alloy light emitters were the earliest progenitors of the now ubiquitous LED and have spawned related devices in a variety of III-V ternary and quaternary materials systems, leading to the continued development of an "ultimate light source"—the high-efficiency injection luminescence source available today in the form of advanced "high-brightness" LED products in the InAlGaP and InAlGaIn alloy material systems.

Today, over 40 years after the first demonstration of the injection laser in September 1962 and the first demonstration of a compound semiconductor alloy device in October of the same year, advances in materials and device design have made the injection laser an essential device in many important systems. High-performance red-emitting InAlGaP

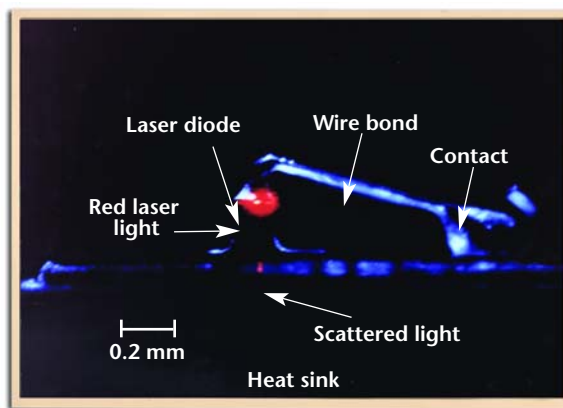


Figure 4. Photograph of one of Holonyak's first GaAsP injection lasers. This is the first direct photograph of a laser diode made using its own photon emission as a light source. The color film is overexposed in the region of the facet where laser operation is occurring. [From N. Holonyak Jr., IEEE J. Quantum Electron. QE-23, 684-91 (1987).]

heterojunction quantum-well DVD lasers, for example, are currently grown primarily by metal-organic chemical vapor deposition and cost considerably less than \$1 in packaged form. It is also interesting to note that GaAsP LEDs, closely related to those first diffused GaAsP diodes, are still produced commercially. And the diode laser has become the dominant form in the commercial laser market, with millions produced each year. We enjoy a multitude of benefits from the early research and development of semiconductor diode lasers, multi-element semiconductor alloys and their derivative heterojunctions. The future seems to hold an even greater variety of applications for these devices and their progeny.

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- Holonyak had forgotten about the infrared converting "snooper scope" that was used by Hall's group at GE, as well as by Rediker's group at Lincoln Labs, to observe the emission patterns from their IR-emitting diode lasers.
- Air Force contract AF 19 (604)-6623.
- However, Hall's GaAs laser work was funded entirely by GE Internal Research and Development funds and all the technical notes and data were recorded in notebooks separate from those used for the Air Force contract research. (R. N. Hall, private communication, Nov. 2002).
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