

Semiconductor Diode Lasers: Early History

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In 1958 Arthur Schawlow and Charles Townes [1] published a seminal paper suggesting how to extend maser action to the visible spectrum to make a laser. Only two years later in 1960 Ted Maiman [2] made the first working laser by exciting R-line emission of ruby with a flashlamp. Shortly thereafter Peter Sorokin and Mirek Stevenson [3] reported a four-level laser in uranium-doped calcium fluoride, which had a much lower excitation threshold, and Ali Javan [4] reported the helium-neon gas laser, which used radio frequency (RF) excitation.

All these lasers suffered from inherent shortcomings, they were large, bulky, and very inefficient at transforming excitation energy into coherent light. Overcoming these difficulties would be crucial because most applications of lasers require compact, highly efficient devices.

Semiconductors offered the possibility of high efficiency and compactness, but it was by no means obvious how to make a semiconductor laser. Many people proposed ideas, but there was no experimental work. John von Neumann was the first to suggest light amplification by stimulated emission in a semiconductor in an unpublished paper in 1953 [5], five years before Schawlow and Townes's groundbreaking paper. Von Neumann suggested using a p - n junction to inject electrons and holes into the same region to achieve stimulated emission, but the scientific community was unaware of his idea. In 1958, months before Schawlow and Townes, Pierre Aigran also proposed stimulated emission from semiconductors in an unpublished talk [6]. At about the same time N. G. Basov, R. M. Vul, and Yu. M. Popov [7] made a similar suggestion. None of these ideas led to any experiments, perhaps because they did not specify what semiconductor or structure or electronic transitions to use.

M. G. Bernard and G. Durafforg [8] then put forth a condition for lasing when electrons dropped from the conduction band to the valence band: the difference between the quasi-Fermi level of electrons in the conduction band, E_{Fn} , and that of the holes in the valence band, E_{Fp} , must be greater than the photon energy ($E_{Fn} - E_{Fp} > h\nu$). More to the point, Basov and co-workers [9] suggested that recombining electrons and holes could produce stimulated emission. However, their work attracted little attention because they said nothing about the crucial matter of which semiconductor to use.

W. P. Dumke [10] in early 1962 pointed out that indirect semiconductors such as silicon and germanium would not work as lasers because the gain from conduction to valence band transitions is not sufficient to overcome the loss from free carrier absorption, which is intrinsic to the material. In contrast, the gain for interband transitions in direct materials such as GaAs is large enough to overcome the loss. That prediction has stood up until the present time, notwithstanding the work of Kimerling and co-workers [11] who made a laser in Ge, which was made quasi-direct by stress caused by epitaxial growth on Si.

By far the most influential work leading to the GaAs injection laser was the observation of interband emission from forward biased GaAs p - n junctions at 900 nm at room temperature and at 840 nm at 77 K. This was first reported at the March 1962 American Physical Society Meeting by J. I. Pankove and M. J. Massoulié [12]. At the same meeting Sumner Mayburg and co-workers [13] presented a post-deadline paper claiming 100% emission efficiency of 840 nm radiation from a p - n junction at 77 K. However, their evidence was indirect—that the light at 840 nm was visible to the eye, indicating that it was very intense, and its intensity was linear with injection

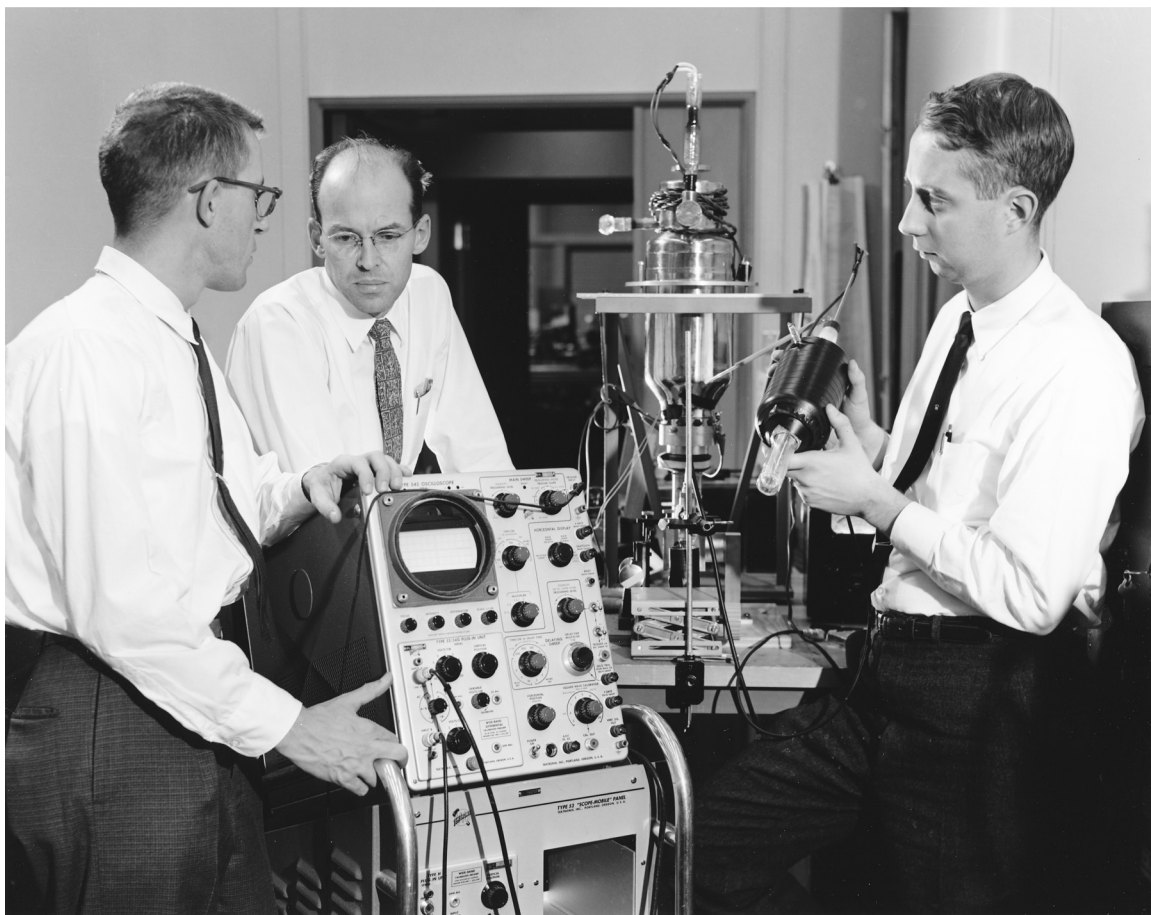


◀ **Fig. 1.** IBM scientists observe electronic characteristics of their new gallium arsenide direct injection laser. From left to right: Gordon J. Lasher, William P. Dumke, Gerald Burns, Marshall I. Nathan, and Frederick H. Dill, Jr. The picture was taken on 1 November 1962. (Courtesy of International Business Machines Corporation, © International Business Machines Corporation.)

current—and less than totally convincing. At about the same time D. N. Nasledov and co-workers [14] in the Soviet Union reported about 20% line narrowing of the radiation from a forward biased GaAs p - n junction. It was an interesting result but was not stimulated emission.

A few months later in June 1962 R. J. Keyes and T. M. Quist [15] presented direct evidence of the high efficiency of the GaAs p - n junction light at the Durham, New Hampshire, Device Research Conference. They measured light intensity as a function of current with a calibrated light detector and found near 100% efficiency for the conversion of electrical energy to optical energy. This work got wide attention, with an account published the day after the conference presentation in *The New York Times*. The management at several industrial research laboratories took notice, and activity in GaAs emission increased substantially.

It was barely four months later that laser action in GaAs was reported at four separate laboratories within five weeks of one another. The first two reports were published simultaneously on 1 November 1962. R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson [16] from General Electric in Schenectady, New York, had a received date 11 days before M. I. Nathan, W. P. Dumke, G. Burns, F. H. Dill, Jr., and G. J. Lasher [17] from IBM in Yorktown Heights, New York (see Figs. 1, 2, and 3). The GE paper was more complete in that it demonstrated an actual laser structure, shown in Fig. 1(a) of that paper (not reproduced here). The laser oscillated in the plane of the junction and emitted coherent light from the polished end faces. On the other hand the IBM paper reported line narrowing in an etched diode. One and a half months later two more



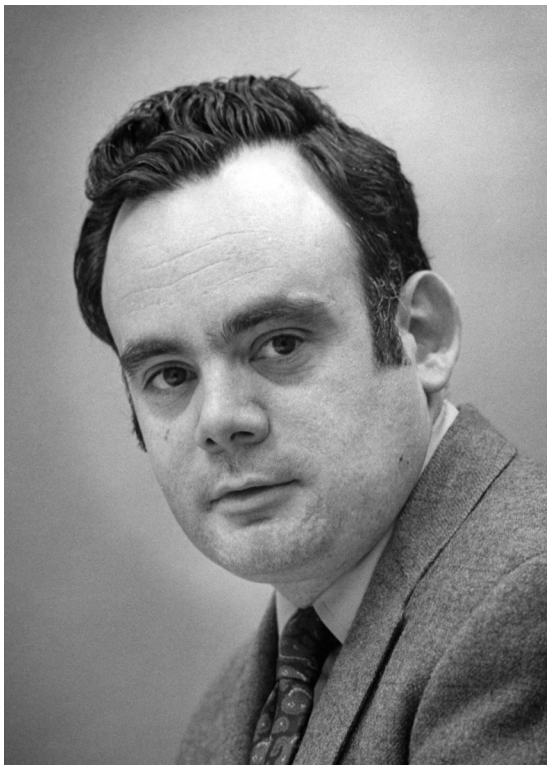
▲ **Fig. 2.** Gunther Fenner, Robert N. Hall, and Jack Kingsley at GE Research & Development Laboratories with the first diode laser, which operated in the dewar that Kingsley is holding. (General Electric Research Laboratories, courtesy AIP Emilio Segre Visual Archives, Hecht Collection.)

papers from different laboratories were published: N. Holonyak, Jr., and S. F. Bevacqua [18] from General Electric in Syracuse, New York, and T. M. Quist, R. H. Rediker, R. J. Keyes, W. E. Krag, B. Lax, A. L. McWhorter, and H. J. Zeiger [19] from Lincoln Laboratory in Lexington, Massachusetts.

All four lasers operated at 77 K in a pulsed mode with a pulse length of about 100 ns and a repetition rate of about 100 Hz, and the emission of three of them was about 840 nm. The GE Syracuse work was different from the others in that the laser light was visible, near 660 nm, and the laser material was a semiconductor alloy, GaPAs. It was remarkable in that the GaPAs material was polycrystalline, but still recombination radiation was so efficient that it lased. The IBM group achieved full-fledged pulsed laser operation at room temperature and continuous operation at 2 K in short order as reported in several papers in the January 1963 issue of the *IBM Journal of Research and Development* [20–26]. A key advance of the IBM group was the first use of cleaved ends of the lasers by R. F. Rutz and F. H. Dill [27]. This greatly simplified the fabrication process.

The publication of the four papers from GE, IBM, and Lincoln Lab launched a tidal wave of research activity on semiconductor lasers. Just about every industrial and government research laboratory and many university laboratories initiated work in the area.

The threshold current density of early semiconductor lasers operating at 77 K was several thousand A/cm². The threshold current was so high that the laser could operate only under short (~100 ns) excitation. When the lasers [28] were cooled to 4.2 K, the threshold went down to less than 100 A/cm² and the laser operated continuous wave (CW). As the temperature was increased, the threshold current



▲ Fig. 3. Marshall I. Nathan. (Courtesy AIP Emilio Segre Visual Archives, Physics Today Collection.)

increased rapidly until at room temperature it approached 10^5 A/cm^2 . Work to reduce the threshold current by improving the geometric structure and the impurity doping profile proceeded. By heroic efforts at heat sinking and optimizing the laser structure limited CW operation was obtained at temperatures as high as 205 K [29]. However, the high threshold and the pulsed operation placed serious limitations on the possible application of semiconductor lasers. Much work needed to be done.

It was clear that poor guiding of the laser light in the active region p - n junction caused the high threshold. The light was spreading out into the inactive regions of the structure, where it was being lost to diffraction and being reabsorbed. The guiding due to the population inversion was very weak. Manipulating the junction profile improved the situation some, but not enough to get to CW operation at room temperature. Better guiding could be obtained for modes perpendicular to the p - n junction because of the larger cross-sectional area. However the active region is so thin for this direction of propagation that the overall gain would be very low, and the losses in the unexcited regions of the laser would be very large. At that time a laser of this type was impractical.

In 1963 Herb Kroemer [30] suggested that improved guiding could be obtained by using different materials for the active layer and the adjacent cladding layers, creating heterojunctions on either side of the active layer. This structure came to be known as the double heterojunction laser. If the cladding layers had a lower index of refraction than the active layer, the guiding would be improved substantially. This could be accomplished by using a material with a higher energy gap for the cladding layers since the index decreases with increasing energy gap. This index difference would be much larger, and hence, the wave guiding would be much better in the heterojunctions than in a homojunction. Furthermore, the loss due to re-absorption of the laser light in inactive cladding layers would be reduced because of the higher energy gap in the inactive cladding.

One material choice Kroemer suggested was using Ge, an indirect semiconductor, as the active layer and GaAs in the cladding layers. This is an excellent choice for crystal growth because Ge and GaAs have the same lattice constant. With the direct gap in GaAs only 0.14 eV higher than the indirect gap in Ge, Kroemer hoped the population in the direct gap material would be sufficient to get lasing. This turns out not to be the case, although as mentioned earlier Kimmerling and co-workers [11] made a Ge laser by using growth-induced stress to make the direct gap closer to the indirect gap.

Alferov and R. F. Kazarinov [31,32] in the Soviet Union had similar ideas for heterojunctions. They made lasers with GaAs active regions and GaPAs cladding layers, but the lattice mismatch between the two materials made their lasers polycrystalline so they had high-threshold current densities.

Clearly, what were needed were direct gap materials with sufficiently different energy gaps so as to provide a single crystal heterojunction with good mode guiding for the laser. This came in 1967 from Jerry Woodall and Hans Rupperecht [33] at IBM, who were working on solar cells, where they wanted a large energy gap to let more light into the p - n junction in smaller-gap material. Using the alloy system AlGaAs, which has a good lattice match to GaAs, they made single-crystal AlGaAs/GaAs heterojunctions. They grew their crystals with liquid phase epitaxy, which had been invented by H. Nelson [34] several years earlier and later became commercially important. They observed efficient electroluminescence. However, they did not apply their technique to lasers.



▲ Fig. 4. Future Nobel Laureate Zhores Alferov (lower right) with colleagues (clockwise) Vladimir I. Koro'kov, Dmitry Z. Garbuzov, Vyacheslev M. Andreev, and Dmitry N. Tret'yakov, the group that made the first CW diode laser. (Zhores I. Alferov, courtesy AIP Emilio Segre Visual Archives, Hecht Collection.)

This was left to H. Kressel and H. Nelson [35], who in 1967 reported an AlGaAs/GaAs single-heterojunction laser (structure shown in Fig. 1(b) from that paper [not reproduced here]) with its active region in the p -type region of the GaAs. Because of the improved guiding and reduced absorption of the AlGaAs the laser's threshold current density was 8000 A/cm^2 , a factor of two to three times lower than the best homojunction lasers at the time. Shortly thereafter similar work was done by Hayashi, Panish, Foy, and Sumki [36,37], who obtained a threshold current density as low as 5000 A/cm^2 . However, these results were not good enough to obtain CW operation at room temperature.

Room-temperature continuous operation would take a further advance, namely, the double-heterojunction laser, shown in Fig. 1(c) from that paper (not reproduced here), in which the large-gap AlGaAs material is on both sides of the junction, providing better mode guiding and reduced loss on both sides of the junction. The heterojunctions also confine the electrons and holes to a thin region, yielding higher gain. The first double-heterojunction lasers were made by Alferov, Andreev, Portnoi, and Trukan [38] in 1968. These lasers had threshold current density as low as 4300 but were not yet CW. In 1969 Hayashi, Panish, and Sumski [36] reported the achievement of double-heterostructure AlGaAs/GaAs lasers with a threshold as low as 2300 A/cm^2 [39] By the following year (1970) they had reduced the threshold down to 1600 A/cm^2 and obtained CW operation at room temperature [40]. Alferov's group (see Fig. 4) achieved CW room temperature operation at about the same time in a stripe-geometry laser [41].

At this point it was clear that the semiconductor laser was a device with many important applications. Research and development toward this end have continued and expanded since then.

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