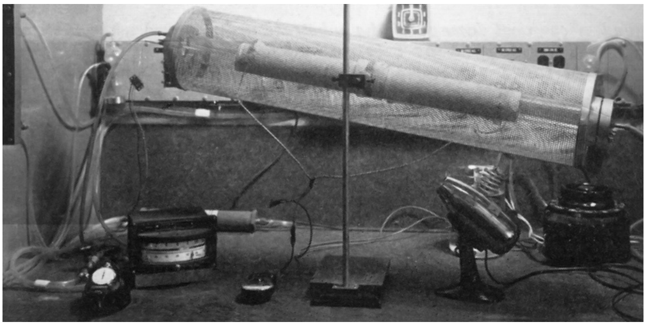
Advent of Continuous-Wave Room-Temperature Operation of Diode Lasers

Michael Ettenberg

The story of getting to room temperature continuous-wave (CW) operation of semiconductor diode lasers will start when the author arrived at RCA Labs with a fresh Ph.D. in June of 1969. RCA had decided that GaAs would be the next important semiconducting material in the solid-state electronics business after germanium, which at the time was the most prevalent transistor material. While silicon transistors were already being manufactured, GaAs transistors would be far superior, and RCA Research Lab researchers would concentrate their efforts on GaAs and related compounds to leapfrog silicon. The choice had some validity. GaAs was a direct-band semiconductor and thus had shorter electron hole lifetimes and a larger bandgap, making possible transistors with higher speed, less temperature dependence, higher operational temperature ranges, and smaller size. While all this is true, silicon became the pervasive electronic device material for a variety of good reasons that will not be detailed here. But GaAs and its related direct bandgap materials could do something that silicon could not do, that is, emit light efficiently. So RCA Labs moved its GaAs efforts to develop LEDs and diode lasers.

The author's first assignment was to grow AlAs epitaxially on GaAs single-crystal substrates via vapor-phase epitaxy, where Al is transported by passing HCl gas over Al and As is supplied by breaking down arsine. After AlAs growth characterization, devices became of interest. Since it seemed easier to make devices out of new materials than to create the materials themselves, the author joined a group headed by Henry Kressel working on laser diodes. These small devices were fascinating, as they were able to put out large amounts of reasonably directed light, albeit they could be seen only with a night vision scope. There were four relatively large research efforts at the time: Bell Labs the largest by far, Standard Telecommunications Laboratory (STL) in England, RCA Labs, and the Russian effort, about which less was known, mainly due to the cold war. At IBM, GE, and Lincoln Labs, even though diode lasers were first demonstrated there, research efforts were not substantial. The research projects at Bell Labs and STL were considerable, supported by telephone usage; telephone companies were utilities at time. The telephone giants first saw lasers as a potential source for free-space communications, a secondary effort compared with microwave transmission in air and pipes until Charles Kao envisioned optical communications in fibers [1] and research at Corning demonstrated low-loss optical fibers in 1970 [2]. Then the laser efforts intensified. RCA's research was driven by other applications such as optical disc recording and playback and military usage. Since RCA had an Aerospace and Defense division, the diode laser efforts could be justified, but RCA as a corporation was focused on television, and lasers were not a mainline effort. The research was about half supported by the corporation and half by government research contracts. The first applications of laser diodes were military in nature, and RCA decided to make the devices commercially so they could supply them to their defense customers and potentially lower the price by supplying them for other commercial uses. In 1969 RCA became the first commercial supplier of laser diodes, although it was a miniscule business, especially for a multi-billion-dollar corporation.

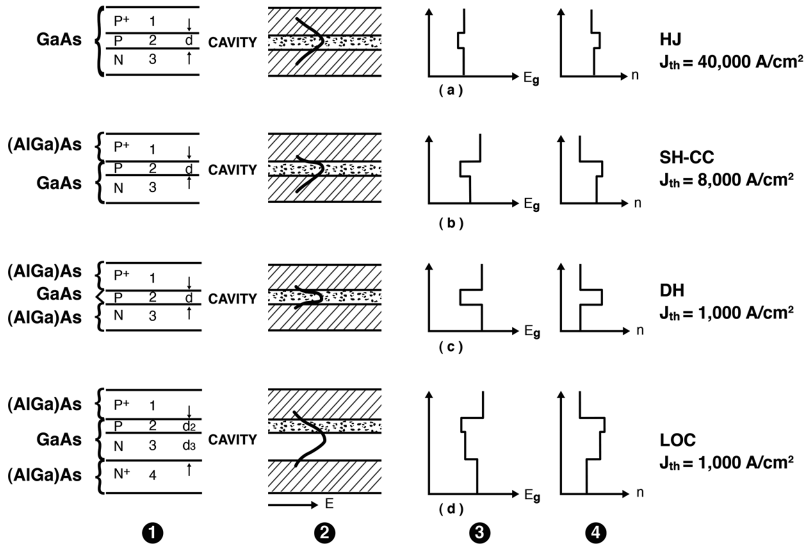


▲ **Fig. 1.** First liquid-phase epitaxy (LPE) growth apparatus for creating laser diode (tipping furnace). (H. Nelson, RCA Rev. **24**, 603 [1963]. Courtesy of Alexander Magoun.)

The author was introduced to diode lasers by Herb Nelson, who invented liquid-phase epitaxy (LPE) the process used to fabricate lasers throughout their initial development, well past the first CW demonstrations and many years beyond, through the first several years of CD player manufacture. Today almost all lasers are made by metal organic chemical vapor deposition (MOCVD): a much better controlled process and one that can be readily scaled up to multiple large wafers. What Herb demonstrated was called a tipping furnace (as shown in Fig. 1); it was a tubular furnace about six inches in diameter mounted in a metal cage. The cage was in turn mounted in a seesaw arrangement at the center of the furnace so the furnace could be rocked back and forth or tipped. Inside the furnace was a sealed quartz tube with hydrogen flowing through it and a carbon boat; at one end of the boat was a small polished single-crystal GaAs wafer of about a square centimeter, and at the other end of the boat was a polycrystalline GaAs wafer with a glob of gallium on it. The process started with the furnace being heated to about 800°C with the polycrystalline GaAs and Ga side lower, and some time was allowed so the GaAs could go into solution in the Ga until saturation; then the furnace was tipped the other way and the saturated Ga rolled onto the single-crystal wafer. Next the furnace was cooled and the GaAs in solution precipitated onto wafer to form an epitaxial layer on the single crystal. This epitaxial layer was much superior in terms of contaminants and defects to the underlying substrate and was also superior in terms of its luminescent properties and ability to make lower-threshold, more efficient lasers. Al was added to the Ga glob so that AlGaAs alloys could be grown. Al and Ga atoms are about the same size; therefore dislocations caused by lattice parameter mismatch would not be formed when AlGaAs was grown on GaAs. In addition, adding Al to GaAs raised the bandgap and lowered the index of refraction of the alloy compared to GaAs, which proved to be crucially important to the creation of low-threshold efficient lasers. The temperature was controlled by hand, using a variable transformer to control the current to the furnace and a 0–1000°C dial thermocouple readout. It was amazing how such a crude growth system could produce such sophisticated devices, but Herb understood the materials and was an artist. Later the process was brought under better control using carbon boats with a wafer that slid under multiple bins to allow growth of multiple layers with controlled composition and remarkable submicrometer-thickness accuracy.

The first diode lasers were simply millimeter-sized cubes of GaAs containing a diffused *p–n* junction with polished faces for mirrors that operated at liquid nitrogen temperatures with multi-amp very-low-duty-cycle short pulses applied. It was remarkable that these devices lased, considering that all prior laser types required tens of centimeters of cavity length and mirror reflectivity greater than 95%. The gain in GaAs per unit length was exceptional, thus allowing the gain to exceed the loss even though the reflectivity at the natural mirror surface of GaAs is only about 30%. The applied current to these first devices was many tens of thousands of amperes per square centimeter at liquid nitrogen temperatures; the threshold current increased exponentially as the temperature increased, so room temperature CW lasing was a long way away. It was found early on that GaAs cleaved nicely on the 100-crystal plane, so the lasers were grown on single-crystal wafers cut on the 100 plane. Then the mirror facets could be easily formed after the wafers had been thinned, metalized on the *n* and *p* sides by cleaving into bars. Next the bars were sawed into individual dies about 400 μm in length between the mirrors and 100 μm wide. The sawn roughened sides prevented lasing from occurring crosswise to the mirrors.

There were three important steps to room-temperature CW lasing: the addition of heterojunctions to the laser structure, the double heterojunction, and finally, the stripe contact. In 1969 independently and simultaneously, Kressel and Nelson [3] and Panish *et al.* [4] published papers demonstrating that adding heterojunctions of AlGaAs on GaAs and diffusing the *p–n* junction a micrometer or so from the

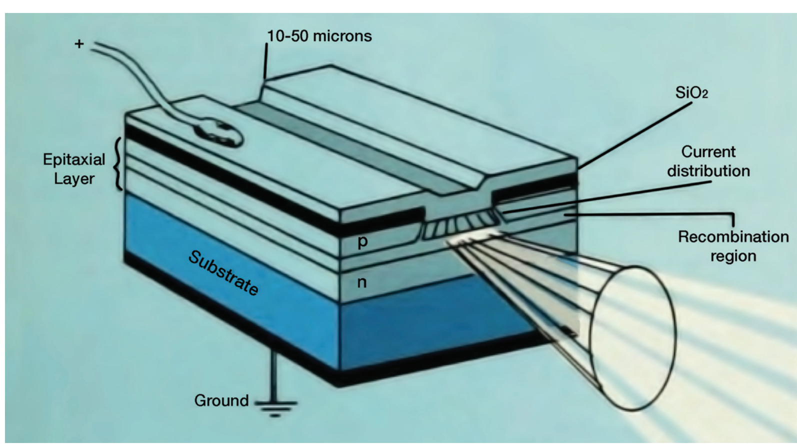


▶ **Fig. 2.** Schematic cross section of various laser structures showing the electric field distribution E in the active region, variation of the bandgap energy Eg, and variation of the refractive index *n* at the lasing photon energy. (a) Homojunction laser made by liquid phase epitaxy, (b) single-heterojunction "close-confined laser," (c) double-heterojunction laser, and (d) large-optical-cavity (LOC) laser. Figure 5 from H. Kressel, H. F. Lockwood, I. Ladany, M. Ettenberg, Opt. Eng. **13**, 417–422, 1974. (©1974 SPIE reprint_permission@spie.org.)

heterojunction formed a light waveguide. This waveguide confined the light, creating electron/hole recombination to that waveguide as illustrated in Fig. 2 [5]; consequently, the threshold current could be reduced to about 10,000 amps/cm^2, still a factor of 10 or so away from what would be needed for CW operation. The reduction in threshold from the simple *p-n* homojunctions came from the fact that the light and the recombination of electron and holes was confined to a smaller volume, thus requiring less current to invert the population to the point of lasing. These single-heterojunction devices were the first laser diodes to go into production, becoming optical proximity sensors for the sidewinder missile.

Art D'Asaro and colleagues [6, 7] at Bell Labs developed the stripe contact, shown in Fig. 3, which is a necessary and enduring feature for laser diodes, because it not only stops the cross lasing in a simple manner but facilitates the heat sinking of the device with unpumped regions all along the laser cavity.

The final and most important step came from Alferov *et al.* [8]. Alferov was one of the leaders in the field and came to United States to visit RCA and Bell Labs, among others. The visit was memorable, because it was very strange. We sat in a small office and discussed the progress of lasers. Alferov had a large heavyset man with him who said very little and seemed to know little about lasers; it was surmised that he was KGB. Alferov did not disclose the double-heterojunction laser structure nor was he shown much because the work was partially supported by Department of Defense. It was learned later that he did discuss the double-heterojunction work at Bell Labs, probably because they were more open. There was a race to achieve CW operation. Bell and RCA Labs were neck and neck, but Bell had the stripe-contact technology and learned about the double-hetrojunction structure. As a result, Hayashi and



▶ **Fig. 3.** Schematic of a typical CW heterojunction laser, drawn upside down to show the stripe contact. Diffraction causes the vertical spreading of the beam. Reproduced with permission from Fig. 6 of H. Kressel, I. Ladany, M. Ettenberg, and H. Lockwood, Physics Today **29**(5), 38 (1976). (Copyright 1976, American Institute of Physics.)

Panish [9] won the race to CW. The addition of the second heterojunction forced the light and electron/hole recombination to be confined to a few tenths of a micrometer and allowed thresholds close to 1000 A/cm^2, which together with the stripe-heat sinking allowed CW operation at room temperature. But it was CW in name only. The initial devices lasted only minutes.

To be useful the devices had to live for many thousands of hours, and here the author was able to make a contribution. One of his first projects on lasers came from a suggestion by Herb Nelson. He said they were evaporating SiO_2 followed by gold as mirrors on the back facet of the devices to make them emit out of one end; many of the devices were shorting probably due to pinholes in the oxide. Could the process be improved? A multi-layer dichroic reflector was eventually developed consisting of Si and Al_2O_3 as the reflector and an Al_2O_3 passivating and reflectivity control layer on the emitting facet [10]. The lifetime of AlGaAs lasers operating at low power was steadily increased to more than a million hours median time to failure [11, 12] by growing on low-dislocation substrates to eliminate defects inside the laser and applying the aforementioned passivating optical coatings to the emitting facets. Such devices helped create the early fiber-optic communications systems and were the light sources for CD and DVD players.

The final steps to today's modern laser diode were separately confining the light and the electron/hole recombination first described by Lockwood *et al.* [13] as shown in Fig. 2 and the understanding by Yariv *et al.* [14] that by making the electron/hole recombination very thin (a few tens of nanometers), quantum effects would come into play and the gain would substantially exceed what might be expected for such thin layers. The changes allowed the threshold current to be reduced to close to 100 A/cm^2, allowing lasers to be fabricated with electricity-to-light conversion efficiencies exceeding 75%. These lasers, called separate confinement heterojunction quantum well lasers, are the most reliable and efficient light sources known to man and continue to change our world.

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