Research at Lincoln Laboratory Leading up to the Development of the Injection Laser in 1962

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(Invited Paper)

Abstract—**In 1958 the semiconductor device group at Lincoln Laboratory began to concentrate its efforts on exploiting GaAs. These efforts, in addition to yielding diodes with ns switching speeds, led to the development in early 1962 of diodes which emitted near-bandgap radiation with very high efficiency, and to the development in October 1962 of the diode laser. The theory of the semiconductor laser developed at Lincoln Laboratory in the mid-to-late 1950's provided the foundation necessary for the design of the diode laser structure after the highly efficient production of near-bandgap radiation was demonstrated.**

Introduction

IN A previous paper [1], the work at Lincoln Laboratory on the invention and early development of semiconductor lasers was reviewed. In this paper, I will present in more detail the history of the research, both experimental and theoretical, that led us to be one of the four groups to demonstrate the laser within a short interval of time in 1962.

Early Work on GaAs Diodes

It all started with my decision, supported by management, that my small semiconductor device group could make a larger contribution to the field if we did not follow the mainstream of device research in switching from germanium to silicon. We decided in 1958 to switch to gallium arsenide with its promise of higher speed because of its higher mobility and of lower "leakage" current because of its higher bandgap. Later that year, I visited Professor Welker at Siemens, Erlangen, West Germany, who was the expert on GaAs, and he reaffirmed our view on the future applicability of this semiconductor. After obtaining our first GaAs material from RCA Laboratories with the help of the Wright Air Development Center, we developed techniques using zinc diffusion into n-type wafers to make diffused p–n junction diodes. I always remember my being initially surprised by the metallic droplets that "miraculously" appeared after our first diffusion in a vacuum ampoule. Of course, the arsenic had evaporated since we did not have an arsenic atmosphere, and the droplets were gallium. We solved this problem at the time by including crushed GaAs to produce the arsenic atmosphere in the ampoule. Our first GaAs paper, presented in May 1959 [2], reported 3 ns diode switching time. Obtaining the data was a challenge; I spent over two days synchronizing the sweep of the then state-of-the-art traveling-wave oscilloscope. Further results were reported in the fall of 1959 [3] and the written publication appeared in 1960 [4].

In the fall of 1960 we published [5] data on diodes with reverse leakage currents of about 10^{-12} A, using GaAs that was now being grown for us by Alan Strauss' group at Lincoln. While Jack Lowen and John Halpern worked with me in this early research, by mid-1960 Ted Quist joined the GaAs program. We decided to also investigate GaAs alloy diodes and presented a paper on these diodes at the Solid State Device Research Conference in June 1961 [6]. The electrical properties of the alloy diodes differed from those of the diffused diodes, and I suggested to Quist that we should look as a diagnostic at the recombination radiation of both types of diodes.

Highly-Efficient Production of Near-Bandgap Radiation

Quist went to Bob Keyes, who was doing research using a prism spectrometer, and Keyes agreed to look at the luminescence. The forward-bias luminescence from the diffused diode pinned the recorder and the servomechanism that actuated the recorder was churning. Keyes had to increase the full-scale setting of the recorder by at least 3 orders of magnitude and close the spectrometer slits to near zero to bring the reading back on scale. Keyes then calculated the efficiency at which this near-bandgap radiation was being produced. He remembers that the result of this first calculation was 125 percent! Further refinements reduced it below 100 percent. Even so, when he gave his paper reporting up to 85 percent efficiency at 77 K at the Solid State Device Research Conference in July of 1962 [7], Hank Summers commented from the audience that we had violated the second law of thermodynamics. After Keyes answered that he was sorry (he had a sense of humor!), Bob Hall, who was also in the audience, explained why the data did not violate the laws of physics. The results on the efficient production of near-bandgap radiation were published in August 1962 [8].

Once we discovered the high-efficiency in the near-bandgap recombination radiation of injected holes in diffused diodes, we realized that a laser might be possible. (We should have realized that Hall would also come to the same conclusion.) We went to see Herb Zeiger, who was a theoretician in our division at Lincoln, and who was

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a student of Charles Townes and coauthor of the original maser paper.

Early Work on the Theory of Semiconductor Lasers

It was natural, considering the programs at Lincoln, to combine the concepts of semiconductors and masers, and as early as the mid-1950's Zeiger, Ben Lax, Alan McWhorter, Stan Autler, and Bill Krag considered a number of schemes. Both optical and electrical pumping schemes were considered, and the use of Fabry–Perot resonators was suggested by the use of these elements in the millimeter wave effort at Lincoln. Among the maser systems discussed and subsequently reported by Lax in September 1959 [9] were cyclotron resonance masers and masers excited by breakdown of impurities in semiconductors. In this paper, the idea of a p–n junction injection maser in a direct gap material was mentioned.

In a Lincoln Solid State Research Report in October 1959 [10], Zeiger and Krag considered semiconductor masers in three categories: 1) those having initial and final states associated with the same band edge, 2) those between states associated with two band edges separated by a direct gap, and 3) those between states associated with two band edges separated by an indirect gap. A general expression was given for the gain per unit length produced by population inversion in terms of an integral over the distribution of occupied and unoccupied states (equivalent to the now familiar expressions).

The Diode Laser

When we showed Zeiger our high-efficiency results, he was excited and immediately told us about the theory on laser action he had developed in 1959. It was he who suggested the geometry that we should use in our experiments to obtain lasing: that we should fabricate the diodes as rectangular parallelepipeds, have the lasing occur in the plane of the junction, have the short sides polished optically flat and as parallel as possible, and look for lasing with these short sides acting as cavity mirrors. Lax, who headed our division, actively and enthusiastically supported our program to achieve the semiconductor laser at the near-bandgap wavelength. McWhorter was instrumental in developing the electromagnetic mode theory of the operation of the laser. The guided waves were amplified in the thin region along the plane of the junction where there was gain because the population was inverted and then reflected from the cavity ends.

Our major experimental problem was to produce the extremely small, by the standards of 1962, rectangular parallelepipeds with the short sides optically flat and parallel. Almost all the experimentalists, and even Zeiger, remember trips to outside companies who were experts in polishing (but not GaAs!). Finally with fixtures that were complex for us at the time, we produced the required geometry in-house. As Quist has remarked, it would have been wonderful if the sample (with or without the fixutre) had been dropped on the floor so we might have realized

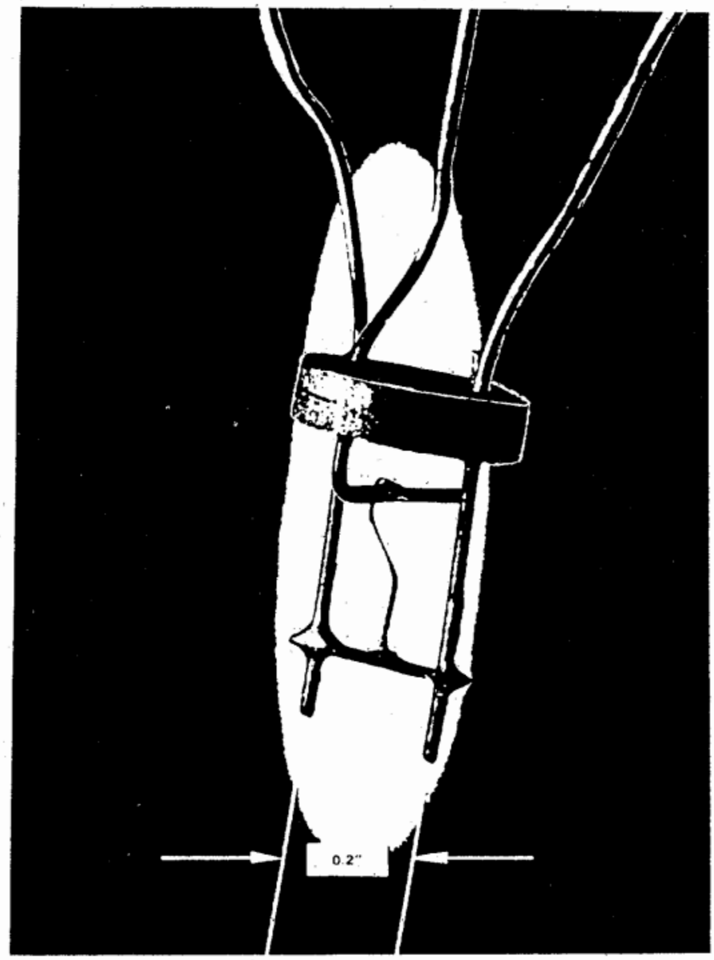

Fig. 1. A photograph of our first diode laser. The laser is mounted on the tab towards the bottom of the photograph. A then-conventional transistor header was used with its three leads going to the top of the photograph. The tab and the n-side of the p–n junction are connnected to two of the header leads. A wire goes from p-side to the other header lead.

the advantages of cleaving. We now need a grating spectrometer, and Krag, who was operating such an instrument, enlisted in the program. The grating instrument was essential so we could distinguish superadiance from lasing. We obtained help Lincoln-wide, and Dick Baker and others in his group designed and built for us the required current pulser.

We also undertook what turned out to be a major diversion from the laser program. It was believed to be important to show the communications potential of the existing high-efficiency light-emitting diodes. Keyes calculated the range and bandwidths possible, and I obtained permission in writing from the local PBS station to rebroadcast their signal at 350 THz (as required by FCC rules at the time). We first demonstrated TV transmission 84 m across the rooftop [11] and then 50 km from the top of Mt. Wachusett to the Lincoln roof [12]. The results were sufficiently newsworthy to be picked up by *Time* magazine [13]. (The last sentence of the 1963 article by *Time* was: "If the world is ever afflicted with a choice between thousands of different TV programs, a few diodes with their feeble beams of infrared light might carry them

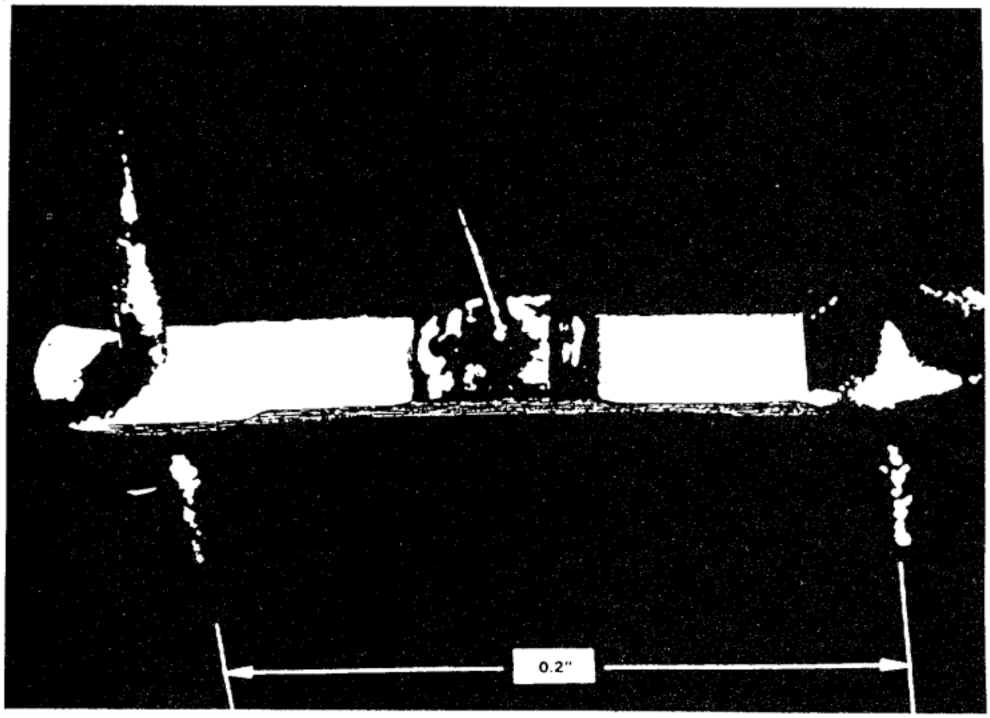

Fig. 2. Closeup of the tab in Fig. 1. This figure is a slightly touched-up version of a photocopy. The negative and glossy prints of this 25-year old photograph have been lost.

all at once.'') I distinctly remember telling Lax that the laser effort was suffering because instead of working on the laser, the team was working on rooftops and mountain tops. I admit that I was not very strong in arguing that this diversion would cause any problems in the long run. We had underestimated the competition!

In September, the required geometry for the laser had been produced. We also had quite a few good wafers with zinc-diffused p–n junctions from which diodes had been fabricated which emitted spontaneous radiation with high efficiency. Early in October late on a Friday, Quist saw (with an infrared viewer) what appeared to be intense filaments in a laser-type structure. I remember Lax telling us that we should not allow a weekend to delay our investigations. Quist and I came in on Saturday and obtained the data that proved that we had achieved our objective, that the junction diode was a laser emitting coherent radiation. We submitted a paper (subsequently divided into experimental [14] and theoretical [15] parts) reporting the results to *Applied Physics Letters* on October 23, 1962.

Fig. 1 is a photograph of the injection laser used to take the data that first Saturday. The three leads of the header are at the top of the picture. The tab on which the n-side of the laser is mounted is at the bottom of the picture supported by and electrically connected to two of the leads. A wire connects the contact to the p-side to the other header lead. Fig. 2 is a closeup of the tab, and Fig. 3 is the perspective drawing we used at the time to describe the geometry and some of the fabrication details.

Bob Hall, Marshall Nathan, and I were aware of the

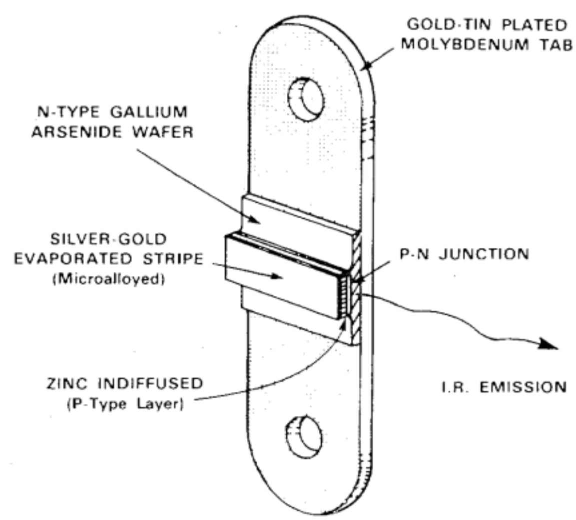

Fig. 3. Perspective drawing showing the geometry and some of the fabrication details of our first diode laser.

demonstration by each other's group of the junction laser by the time the 1962 International Electron Device Meeting was held at the end of October. The first publication on the laser was scheduled for November 1. I well remember the three of us sitting in the foyer outside the meeting rooms, concerned that one of the three groups would try to scoop the others by announcing the laser. All three of us, who have remained the very best of friends from before 1962 to this date, were parrying to make sure that none of our laboratories which had papers on the program would use the occasion for the announcement. None did.

Epilogue

The year 1962 was scientifically exciting and fun to live. I always regretted the subsequent controversy, never to my mind engendered by the principals, on priority. In December of that year, I placed on top of our group Christmas tree a blinking semiconductor laser. We had an infrared viewer to the west of the tree and a sign proclaiming that "the light from the East is coherent." I checked with Hall, Nathan, Holonyak, and any others of whom I could think and ascertained that they had not similarly decorated their trees. I have told all who ask me about priority that we were, without a doubt, the first to have a Christmas tree with a blinking coherent light.

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In 1951 he was employed by the M.I.T. Lincoln Laboratory where he worked on semiconductor devices. He was one of the original workers in the field of GaAs devices and was a member of the team that developed the high-efficiency GaAs light-emitting diode and the GaAs laser diode. He was Professor of Electrical Engineering at M.I.T. from 1966 to 1976, Adjunct Professor from 1976 to 1982, and Senior Research Scientist since 1982. His work on the M.I.T. campus has centered on optoelectronic semiconductor devices. From 1970 to 1972 he was Associate Head and from 1972 to 1980 Head of the Optics Division at Lincoln Laboratory. In 1980 he returned to research at Lincoln Laboratory where his work has centered on guided-wave optoelectronic devices.

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