An Introduction to the Development of the Semiconductor Laser

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Abstract—In late 1962, the first semiconductor injection lasers were reported. While earlier workers had considered the possibility of light amplification in semiconductors, the achievement of high-efficiency electroluminescence from forward-biased GaAs p-n junctions was the event that catalyzed and accelerated efforts to demonstrate a semiconductor laser. This paper will attempt to review the experimental and theoretical work that preceded the actual demonstration of the semiconductor diode laser.

INTRODUCTION

In late 1962, four groups reported the operation of homojunction semiconductor injection lasers. These first reports are listed below in chronological order of their received dates.


The work that led up to the achievement of injection laser operation at these laboratories is discussed elsewhere in this Special Issue of the IEEE JOURNAL OF QUANTUM ELECTRONICS. This paper will discuss the work concerning the semiconductor laser prior to the demonstration of injection laser diodes in 1962 and attempt to describe various early theoretical and experimental efforts to make the semiconductor laser a reality. The author realizes that many different perspectives exist on this subject. Since only a few historical review papers exist describing the efforts at various research labs, it is difficult to determine exactly what ideas were being pursued and when the idea of making a semiconductor laser first came into being. For this reason, the authors of the first four papers describing semiconductor laser operation have been asked to write a description of their early ideas and research which led to the achievement of semiconductor laser operation in their laboratories. These papers appear in this issue. Since the early semiconductor laser work of these four groups is discussed in depth in these Invited Papers, their work is not discussed in detail in this paper.

EARLY CONCEPTS OF THE SEMICONDUCTOR LASER

While various ideas concerning the semiconductor laser had been discussed previously by several workers, the first demonstrations of the operation of semiconductor lasers in 1962 were realized without the benefit of many viable suggestions from earlier (i.e., prior to 1962) theoretical and experimental treatments of the concept of the semiconductor laser. The work leading up to the realization of the semiconductor laser has been briefly discussed by several authors. (See for example, [1] and [2].) In addition, the IEEE Press has published a volume in the “Selected Reprint Series” (sponsored by the IEEE Quantum Electronics and Applications Society, now the IEEE Lasers and Electro-Optics Society) on semiconductor lasers [3]. This volume contains reprints of many of the important papers on semiconductor lasers from the period 1962–1978. The first four papers in this book are the four reports listed above.

The first documented discussion of the possibility of light amplification by the use of stimulated emission in a semiconductor (to the best of our knowledge) was made in an unpublished manuscript written by John von Neumann in 1953 [4]. In this paper, von Neumann discussed using carrier injection across a p-n junction as one possible means of achieving stimulated emission in semiconductors. While von Neumann does not explicitly use the term “p-n junction” in this paper, he clearly has this idea in mind since in Sect. X of this manuscript, he calculates the radiative transition rates between two Brillouin zones,
$B_1$ and $B_2$, with electrons in excess of holes in $B_1$ (i.e., n-type) and holes in excess of electrons in $B_2$ (i.e., p-type) [4]. von Neumann sent this manuscript to Edward Teller along with a letter dated September 19, 1953 [4]. This letter and von Neumann’s previously unpublished manuscript titled “Notes on the photon-dis-equilibrium-amplification scheme” appear in this issue of the IEEE JOURNAL OF QUANTUM ELECTRONICS [4]. A summary of the von Neumann manuscript was included in Vol. 5 of the collected works of John von Neumann, which was published in 1963 [5]. John Bardeen summarized von Neumann’s ideas concerning a semiconductor laser in the following way: “By various methods, for example by injection of minority carriers from a p-n junction, it is possible to upset the equilibrium concentrations of electrons in the conduction band and holes in the valence band. Recombination of excess carriers may occur primarily by radiation... The rate of radiation may be enhanced by incident radiation of the same frequency in such a way as to make an amplifier” [5]. It is clear that von Neumann had the idea of Light Amplification by the Stimulated Emission of Radiation (i.e., the concept of a LASER) about a year before the operation of a MASER was first reported by Gordon, Zeiger, and Townes in July 1954 [6].

As far as we know at present, the first suggestion in an international public forum that it might be possible to obtain coherent light from a semiconductor was made by Pierre Aigrain of the Ecole Nornde Superieure in an unpublished paper given in June 1958 [7]. Aigrain had privately discussed the possibility of making a semiconductor laser with Jacques Pankove of RCA Laboratories in 1956 [7]. At about the same time, at the Lebedev Institute in the U.S.S.R. (July 1958), Basov, Krokhin, and Popov independently came up with a similar idea [8]. While these workers suggested that it was theoretically possible to achieve population inversion in a semiconductor, it was still uncertain exactly what semiconductor to use and what types of electronic transitions should be exploited. In addition, the concept of optical feedback and the need for an electromagnetic cavity were not contained in these early papers.

Casey and Panish [2] discuss the history of the injection laser in Ch. 1 of their book and state that the first theoretical understanding of the requirements for the realization of stimulated emission in a semiconductor was developed by Bernard and Duraffourg of CNET and published in 1961 [9]. Bernard and Duraffourg used the idea of “quasi-Fermi levels” to correctly derive the equations which predict the onset of stimulated emission in a semiconductor [9]. They suggested looking for stimulated emission involving direct transitions in the materials InAs or InSb or transitions between the conduction band and the acceptor states of Zn and In in the indirect semiconductors Ge and Si. Although the idea of achieving population inversion in indirect semiconductors was in error, Bernard and Duraffourg were the first to publish a clear account of the requirements for population inversion in a semiconductor p-n junction. However, they did not discuss the idea of optical feedback and thus one important element in achieving laser operation was missing from their work. Their work did have an influence on at least one of the groups that demonstrated laser operation in 1962. In fact, in his historical review paper published in 1976, Hall mentions discussions he had with Bernard on various concepts concerning semiconductor lasers [10].

Another theoretical treatment of the semiconductor laser was published in 1961 by Benoit a la Guillaume and Tric of the Ecole Normale Superieure [11]. In this work, the authors consider three possible types of semiconductor laser transitions: 1) stimulated emission from an excited state to a ground state of an impurity level in an indirect semiconductor, e.g., the impurity As in Ge, 2) laser operation of a degenerate semiconductor having a direct bandgap (the example of InSb is considered), and 3) lasers involving the annihilation of excitons in indirect semiconductors. These transitions result in the emission of two bosons: a photon and a phonon (Si and Ge are considered as examples) [11]. These authors also pointed out the importance of using an optical cavity for longitudinal mode selection and describe the use of a p-n junction for carrier injection with the edges of the semiconductor serving as the mirrors of the optical resonator.

Basov and his group at the Lebedev Institute in Moscow were also considering how to make a semiconductor laser [8]. Basov et al. published a paper in 1959 concerning the possibility of obtaining a semiconductor laser using “negative temperature states” (population inversion) generated by impact impurity ionization under a pulsed electric field [8]. These workers later discarded this idea in favor of the use of a degenerate p-n junction. In 1961, Basov and co-workers discussed the idea of negative temperature states (using the quasi-Fermi level concept) in semiconductor p-n junctions. [12] These workers considered the case of heavily-degenerate junctions (they refer to tunnel diodes). Also, they stated that “the high density of the majority carriers surrounding the region of negative temperature can, apparently, serve as reflecting surfaces, i.e., a ‘resonating cavity’ is formed,” indicating that they understood the waveguiding properties due to refractive index changes resulting from differences in the carrier concentrations at the edges of the active region [12]. Basov et al. suggested the existence of negative temperature states in a semiconductor would be indicated by changes in the I-V curve when the sample is illuminated with light of “suitable frequency” [12]. In addition, they discussed the achievement of negative temperature states in indirect semiconductors [12], [13] and they also referred to Pankove’s work on luminescence from Ge in a discussion of negative temperature states, and the possibility of achieving laser operation in Ge. It appears that as of about 1961, some of the ideas of Basov and co-workers concerning what to look for in a semiconductor injection laser and in what material it should be built were incorrect.

At about the same time as the paper by Basov et al. concerning negative-temperature states in p-n junctions
was submitted to Zh. Eskp. Theo. Fiz. (April 18, 1961), a paper by Adirovich and Kuznetsova (also of the Lebedev Institute in Moscow) was submitted to Fiz. Tver. Teia (received on May 27, 1961) in which these authors discussed the conditions for population inversion in degenerate semiconductors [14]. In this paper, the authors state "...one method of realizing an inverted distribution between bands might be above-the-barrier injection through the p-n junction in tunnel diodes." It is clear that these authors also had the idea of the use of a p-n junction in mind. Adirovich and Kuznetsova determined the low-temperature threshold current densities required for population inversion in p-n junctions in Si and Ge for three different acceptor doping conditions in the p-type material. They estimated that under optimal conditions, laser operation of Ge could occur at current densities much less than 1 A/cm² at 20 K [14]. They reported no experimental work in this paper.

In April of 1962, Nasledov and co-workers at the Ioffe Physicotechnical Institute in Leningrad published a paper (received January 11, 1962) describing a slight narrowing of the "intrinsic recombination radiation" of a GaAs p-n junction [15]. The 77 K spectrum of this diode was observed to narrow from a FWHM of ~255 Å at 10 A/cm² to a FWHM of ~200 Å at a current density of 1500 A/cm². We know now that this was clearly not a laser. Nasledov et al. proposed two possible explanations for this narrowing: 1) stimulated emission, and 2) effects due to internal absorption at shorter wavelengths. These workers state that "the second explanation above is more likely" [15]. While Nasledov and co-workers did not achieve stimulated emission, they did realize that line narrowing was one way of determining if stimulated emission was occurring. The paper by Nasledov et al. does not discuss the quantum efficiency of the GaAs diodes so it is impossible to tell if these light-emitting diodes were of high quality or not.

Another quite different idea for using a semiconductor to produce coherent radiation was proposed by Benjamin Lax of Lincoln Laboratory in 1959 [16]. He suggested that a semiconductor maser in the far-infrared and sub-millimeter wavelength region could be realized by using the cyclotron resonance transitions of electrons in conduction band states that had been split by the application of a large magnetic field [16]. Lax proposed that a non-equilibrium population of electrons could be created in the conduction band by absorption of optical pump radiation. The applied magnetic field would then be tuned to yield energy spacings that corresponded to the modes of the cavity in which the semiconductor had been placed. This would result in cyclotron resonance transitions and the electrons would emit photons of energy corresponding to the field-induced splitting of the energy states. Lax speculated that the most favorable transitions for this cyclotron resonance maser action would be the direct [111] transitions at the L point of the Brillouin zones in Ge or InSb [16]. In the "Conclusion" section of his 1959 paper on cyclotron resonance masers [16], Lax also discussed semiconductor masers emitting in the near-infrared and referred to unpublished calculations by H. J. Zeiger that predicted a very small matrix element for band-to-band radiative recombination in an indirect semiconductor. From these calculations, Lax concluded that radiative recombination across the bandgap in a direct semiconductor is much more efficient than in an indirect semiconductor. Lax stated that the realization of the semiconductor maser is "perhaps...just a question of finding a suitable material" [16].

In addition to the above workers who discussed stimulated emission in semiconductors, there were other workers who patented concepts concerning the laser operation of semiconductors. The earliest known examples are the patents of Yasushi Watanabe and Jun-ichi Nishizawa that were filed in Japan in 1957 [17]. In these patents, the authors describe several schemes of making a semiconductor maser. The authors use an analog of the microwave maser cavity for the electromagnetic resonator and the active semiconductor (Cl-doped Te or B-doped Si are suggested) is inserted into this cavity with electrodes connected to it to inject free carriers. The patent also discusses the use of a p-n junction for increasing the injection efficiency of carriers (generated by the absorption of light from an optical pump) into "the high energy state" of the semiconductor [17].

Another early patent concerning a semiconductor laser is that of William Boyle and David Thomas of Bell Laboratories which was filed January 11, 1960 [18]. This patent discusses laser operation of Si, Ge, GaP, and CdS using stimulated emission from exciton states at low temperatures. They state that "the pumping can be either by the injection of minority carriers across a p-n junction within the semiconductor or by any incident ionizing energy suitable for producing hole-electron pairs in the semiconductor..." [18]. Boyle and Thomas also discuss the requirements of using an optical cavity to achieve optical maser operation and suggest employing "the semiconductor wafer as a mode isolator by treating the surface of the wafer so as to favor selectively the growth of a longitudinal mode" [18]. It is clear that Boyle and Thomas had the concept of injection of minority carriers by the use of an p-n junction and also the concept of forming the optical cavity by using the semiconductor itself as the optical resonator.

The Demonstration of the Semiconductor Laser

In many respects, the papers discussing the theoretical aspects of semiconductor lasers published up to and during early 1962 were useful only in indicating what conditions might be required to observe stimulated emission in a semiconductor. In general, these papers treat direct and indirect semiconductors more or less equally and implied that laser operation of either type of semiconductor was possible. Also, these theoretical papers failed to clearly identify the changes in device characteristics that are expected to occur when stimulated emission occurs in
a semiconductor. As a result, there was no clear understanding of what to expect experimentally when laser operation was achieved.

The principal event that led to the rush for injection laser operation of semiconductor p-n junction devices in 1962 was the achievement of high-efficiency electroluminescence from GaAs p-n junctions. The first report of high-efficiency spontaneous emission from GaAs p-n junctions was made in early 1962 by Sumner Mayburg and co-workers of GTE Laboratories at the “March” Meeting of the American Physical Society [19]. Although Mayburg presented his data in a post-deadline paper at this conference, his results were apparently not published until January 1963 [19]. Of course, by the time Mayburg and his co-workers’ paper was published, the semiconductor laser was a reality and, as a result, the GTE work got little recognition.

The data presented by Mayburg concerning high-efficiency GaAs p-n junction injection luminescence were similar to the results which were presented later by R. J. Keyes and T. M. Quist, and also independently by J. Pankove at the July 1962 Solid State Device Research Conference (SSDRC). Keyes and Quist from Lincoln Laboratory reported on GaAs diodes that had calculated internal quantum efficiencies of 48–85 percent at 77 K [20]. Pankove from RCA Laboratories reported high-speed modulation of a GaAs diode at 200 MHz [21]. Pankove’s diodes had an estimated total internal quantum efficiency of from 0.50 to 1.00 photon/electron at 77 K, but had an external quantum efficiency of only about 1 percent [21].

After the SSDRC, Hall at the GE Research Lab in Schenectady, NY [10], and Holonyak at the GE Advanced Semiconductor Lab in Syracuse, NY [22], went back to their labs and began an intensive study of how to obtain stimulated emission from p-n junctions and also began to think about what it would take to make an electromagnetic cavity to provide feedback into the active region of the diode. Of course, the group of Quist et al. at Lincoln Laboratory was also interested in getting their high-efficiency GaAs p-n junction diodes to lase [23]. In addition, Pankove at RCA was working on making an injection laser in GaAs. (See the reference to Pankove at the end of [7].)

The IBM work on the semiconductor injection laser had started in 1961 but was intensified after the January 1962 visit by Sumner Mayburg to the IBM T. J. Watson Research Center. Mayburg was working on GaAs p-n junctions at GTE and told the IBM workers of the results of his experiments that indicated that the internal efficiency of GaAs p-n junction diodes could be as high as 100 percent [24]. These results excited many of the people at IBM who were interested in the semiconductor laser problem, including William Dumke [24]. Dumke had already been considering the theoretical aspects of semiconductor lasers and had concluded that it might be possible to observe laser action in GaAs [24], [25]. The IBM researchers then started a concerted effort to explore the possibility of making a semiconductor laser in GaAs [24]. The IBM group’s work on GaAs p-n junction lasers was accelerated in response to the reports at the 1962 SSDRC of high-efficiency injection luminescence from GaAs diodes [24].

**Summary of Historical Literature**

It is evident from the above discussion that many claims can be made concerning the first person to have the idea of making a semiconductor laser. It would be difficult to determine exactly what merit there is to each of these claims, since none of the early ideas concerning the semiconductor laser were entirely correct and none of the early workers had the technological problems completely solved. The first documented ideas concerning the requirements of making a semiconductor laser were written by von Neumann in 1953 [5]. Nishizawa’s “semiconductor maser” patents were filed in Japan in 1957 [17]. Aigrain appears to have considered the concept of a semiconductor laser as early as 1956 [7]. Both Aigrain’s first unpublished statements in public [7] and Basov and his co-worker’s first documented ideas [8] concerning population inversion in semiconductors come somewhat later in June and July of 1958, respectively. Boyle and Thomas patented a semiconductor laser in 1960 [18].

With regard to the actual achievement of the operation of semiconductor lasers, none of this early work mattered much. The use of the direct semiconductors GaAs and GaAsP as the materials of choice for the semiconductor injection laser was a direct result of the reports in 1962 of high-efficiency electroluminescence from forward-biased GaAs p-n junctions [19–21]. In most of the theoretical and experimental papers published up to late 1961, there were no obvious materials of choice for the fabrication of semiconductor lasers. In fact, some researchers continued to work on laser operation of Ge even after the papers reporting the operation of GaAs injection lasers were published in 1962 [7], [26]. The early (prior to 1962) theoretical and experimental work on semiconductor lasers is briefly summarized below.

**von Neumann**

It seems safe to say that as far as we know at this time, the first person to propose the concept of stimulated emission in a semiconductor was von Neumann, who developed a theoretical analysis of the use of a semiconductor material as a light amplifier using a p-n junction for the injection of carriers. von Neumann worked on the theoretical aspects of the problem as early as the summer of 1953. In September of 1953, he sent a detailed analysis of the semiconductor light amplifier to Teller. A summary of his unpublished manuscript appeared in the book John von Neumann, Collected Works, Vol. 5, which was published in 1963 [5]. von Neumann’s theoretical work is quite detailed and discusses some of the practical aspects of the problem. (See von Neumann’s complete manuscript, published in this issue.)
**Nishizawa**

Nishizawa claims to have invented the semiconductor laser in 1957 [17]. This claim is based upon Japanese patents issued to Watanabe and Nishizawa [17]. This work was not brought to light outside of Japan until some time after the actual achievements of laser operation in 1962. There were apparently no published attempts to reduce this patent to practice.

**Aigrain**

Aigrain made a verbal presentation of ideas about obtaining coherent light from a semiconductor at a conference in Brussels in 1958. As early as 1956, he had encouraged Pankove to work on the problem of making a semiconductor laser [7]. He did not publish a paper describing these ideas in the proceedings of this conference, and his work on the subject of the semiconductor laser was not published until 1964. I can find no reports of any experimental work on this problem by Aigrain until 1964, when photoluminescence from InAs was reported [7].

**Basov and Co-Workers**

Basov and his co-workers first published in 1958 their ideas concerning “negative temperature states” (population inversion) in a semiconductor using impact ionization for the creation of electron-hole pairs [8]. They first proposed using a p-n junction in a paper published in June 1961 [12]. While this group published many experimental and theoretical papers on light emission from semiconductors, most of their work was on Ge until February 1963 when they first reported a p-n junction laser in GaAs [26], [27].

**Lax**

Lax proposed in 1959 that a cyclotron resonance far-infrared or submillimeter maser could be made using an optically pumped semiconductor placed in a high magnetic field [16]. This device would emit coherent radiation in the far-infrared or submillimeter region. The device was never realized. However, using Zeiger’s unpublished calculations, Lax did suggest in his 1959 paper that direct semiconductors were probably a much better choice for a semiconductor infrared maser than were indirect band-gap semiconductors [16].

**Boyle and Thomas**

In 1960, Boyle and Thomas patented a semiconductor laser based upon radiative recombination of excitons at low temperatures using various schemes for injecting minority carriers, including the use of a p-n junction [18]. They also described the formation of the optical resonator by using the plane-parallel edges of the semiconductor itself for optical feedback.

**Adirovich and Kuznetsova**

These workers discussed population inversion in a degenerate semiconductor p-n junction in a paper published in November 1961 [14]. They treated the specific cases of Si and Ge. No experimental work was reported in this paper.

**Bernard and Duraffourg**

Bernard and Duraffourg [9] published two papers in 1961 that treated the theory of the semiconductor laser using the concept of the “quasi-Fermi level” and derived equations that predicted the onset of stimulated emission. They considered the case of both direct and indirect band-gap semiconductors.

**Benoit a la Guillaume and Tric**

Benoit a la Guillaume and Tric [11] independently published a theoretical paper in 1961 in which they discussed the theory of the semiconductor injection laser and suggested various embodiments of the concept in both direct and indirect band-gap semiconductor materials. They also noted the importance of optical feedback for the realization of a semiconductor laser.

**SUMMARY**

At this time, we believe that John von Neumann in his 1953 manuscript was the first to treat the idea of a semiconductor light amplifier and to treat the idea substantially correctly. Several individuals did work independently on the concept of a semiconductor laser or maser during the middle and late 1950’s and early 1960’s and a number of theoretical and experimental papers were published on the subject of the injection laser prior to the actual demonstrations of injection laser operation in 1962. However, the most important event that led to the drive to make a semiconductor laser from GaAs and direct alloys of GaAsP was the achievement of high-efficiency electroluminescence from GaAs p-n junctions reported in 1962.

**ACKNOWLEDGMENTS**

The author wishes to thank Prof. N. Holonyak, Jr. for interesting private conversations, a preprint of [22], and a copy of the von Neumann manuscript, and Dr. M. I. Nathan for fruitful private discussions and copies of the sources cited in [24]. He also wishes to thank Dr. R. N. Hall and Dr. R. H. Rediker for useful comments and preprints of their papers cited in [10] and [23], respectively. Also, the author is grateful to Prof. J. Bardeen for information concerning the review he wrote of the von Neumann manuscript, and to Dr. H. Lockwood for comments on the manuscript and a copy of the GTE laser patent. Discussions with Dr. M. von Neumann Whitman, and also with Dr. P. Labalme of the Institute for Advanced Study are gratefully acknowledged.

**REFERENCES**


[4] J. von Neumann, “Notes on the photon-disequilibrium-amplification scheme,” an unpublished manuscript written before September 16, 1953. The typed original and two copies (one with additional notations and changes written in pencil) are located in the “von Neumann Collection” of the Manuscript Division of the Library of Congress of the United States, James Madison Memorial Building, Room 103, Washington, DC, and are part of an extensive collection of von Neumann’s correspondence and other works. The collection was donated to the Library of Congress by Dr. M. von Neumann Whitman and the Institute for Advanced Study in Princeton, NJ, where von Neumann had worked for several years before his death in 1957. von Neumann sent a copy of this manuscript, dated September 16, 1953, to E. P. Wigner with a cover letter dated September 19, 1953. The file also contains a copy of the cover letter in which von Neumann states that the manuscript is “the long-promised write-up on amplification,” and that von Neumann had mentioned these ideas to Teller during the summer of 1953. von Neumann’s manuscript and the letter to Teller are reprinted in this issue. See J. von Neumann, “Notes on the photon-disequilibrium-amplification scheme (Vn), September 16, 1953,” in this issue, pp. 659–673.


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