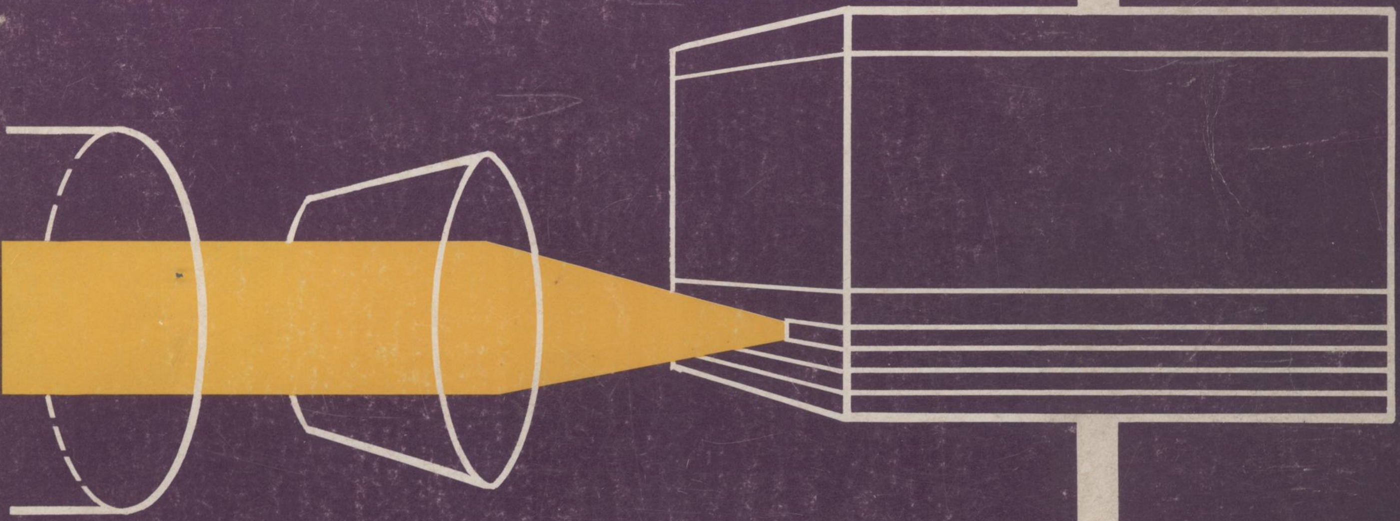
Semiconductor Injection Lasers

Edited by

Jerome K. Butler



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Jerome K. Butler—
Professor of Electrical Engineering
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Introduction

The development of the semiconductor laser as a practical source of coherent radiation has had the effect of increasing the useful frequency spectrum for communication systems. The existence of reliable injection lasers affords the development of economical high-speed channels needed by many telecommunication industries. Solid-state microwave diodes have been pushed to operating frequencies around 10^{11} Hz, which appears to be their theoretical limit. Injection lasers emit radiation around 10^{13} Hz. In addition, while closed-circuit transmission systems use metallic waveguides at microwave frequencies, thin glass-fiber guides are employed at optical frequencies.

The considerable interest in optical communications is reflected in the development of solid-state injection lasers. As a measure of this activity, numerous and significant publications concerning semiconductor lasers have appeared over the last 15 years. Recent books [1], [2] have presented some of the elementary and basic concepts of injection lasers; however, many of the complex details cannot be covered in textbooks and research monographs. Consequently, it is the purpose of this book to bring together a series of the most cogent papers on the development and analysis of semiconductor injection lasers.

Homojunction lasers of GaAs were first fabricated in 1962. These lasers had high threshold currents and operated only at cryogenic temperatures; thus they were impractical for use in communication systems. The promise of the injection laser was later realized with developments of the AlGaAs–GaAs heterojunction, which provided a mechanism for confining both electron-hole pairs and radiation to the neighborhood of the active region. Double heterojunction lasers have very low threshold currents and can be modulated with signals well into the GHz region. Device reliability has been a concern, but fortunately contemporary lasers are approaching many years of life expectancy. These features make them economically possible for transmitter use in high-speed communication channels.

The subjects covered in this volume have been selected with emphasis placed on design, characteristics, and applications of injection lasers. There are many laser devices not covered. For example, distributed feedback (DFB) lasers have received wide interest in recent years because of their important wavelength selection characteristics. However, DFB lasers do not have the life expectancy that contemporary Fabry Perot lasers have and are not widely used in system applications such as fiber-optic links. The collection of papers presented cannot be complete, and the process of choosing the ones in this volume was a difficult task. The initial number of papers chosen was quite large, but because of limited page requirements, that total number had to be significantly reduced. As a result, many excellent papers could not appear in this volume. The series of articles is divided into the following areas.

Part I. Historical: These papers highlight the development of the injection laser from its inception. This series shows that injection laser work was initially done in several laboratories, with their work reported in 1962. The early lasers were relatively inefficient and had large threshold current densities. The primary development of the heterojunction laser was made in the late 1960's and early 1970's.

Part II. Stimulated Emission and Gain: These papers present the fundamental concepts of laser operation common to injection lasers.

Part III. Laser Modes and Structures: This section is designed to familiarize the reader with injection laser modes and contemporary device structures which have direct influence on the modal characteristics. Laser modes appearing in semiconductor devices play a major role in their systems performance. The ultimate aim of a laser design is the fabrication of devices that radiate at a single wavelength with high spectral purity.

Part IV. Electrical and Optical Properties of Laser Materials: This group of papers discusses vital relationships between the laser geometries and operation characteristics such as the threshold current density, the active region gain, and the differential quantum efficiency.

Part V. Degradation: Device reliability is discussed in these papers. It is seen that the continuous development of the material technology has greatly improved device reliability and lifetime.

Part VI. Modulation: The primary attention of these papers is focused on the capabilities of injection lasers for employment in optical communication systems.

Finally, semiconductor laser papers have appeared in numerous journals. However, the most significant concentration of papers has appeared in the IEEE JOURNAL OF QUANTUM ELECTRONICS. There are six special issues on semiconductor lasers:

1. Volume QE-4, April 1968,

2. Volume QE-6, June 1970,
3. Volume QE-9, February 1973,
4. Volume QE-11, July 1975,
5. Volume QE-13, August 1977,
6. Volume QE-15, August 1979.

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[1] H. Kressel and J. K. Butler, *Semiconductor Lasers and Heterojunction LED's*. New York: Academic Press, 1977.

[2] H. C. Casey and M. B. Panish, *Heterostructure Lasers*. New York: Academic Press, 1978.

Part I
Historical

STIMULATED EMISSION OF RADIATION FROM GaAs *p-n* JUNCTIONS*

Marshall I. Nathan, William P. Dumke, Gerald Burns
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(Received October 4, 1962)

A characteristic effect of stimulated emission of radiation[1] in a fluorescing material is the narrowing of the emission line as the excitation is increased. We have observed such narrowing of an emission line from a forward-biased GaAs *p-n* junction. As the injection current is increased, the emission line at 77°K narrows by a factor of more than 20 to a width of less than $kT/5$. We believe that this narrowing is direct evidence for the occurrence of stimulated emission.

The GaAs junctions used in this experiment were made by diffusing Zn into GaAs doped with Te. These diodes were bonded onto a Au-plated kovar washer and the junction was etched to an area of approximately 1×10^{-4} cm^2 as shown in the inset of Fig. 1.[2] No attempt was made to obtain highly resonant electromagnetic modes. The diodes were immersed in liquid nitrogen and driven with current pulses as short as 50 nsec at high current levels. The light output was measured using a Perkin Elmer grating spectrometer and a Dumont 6911 photomultiplier.

At low injection levels, it was observed that more than 95% of the light was emitted in a line at 1.47_3 eV with a width at half maximum of 0.026 eV. From photoluminescence experiments we believe the observed line is due almost entirely to transitions between the conduction band and a Zn acceptor level. It has been theoretically shown that such transitions give rise to a relatively short radiative lifetime for holes trapped by the acceptors.

The quantum efficiency per injected electron was greater than 0.2 and perhaps close to 1 for currents greater than 10 A/cm^2. Similar results have been reported by other workers.[2-4] However, unlike the previously reported measurements,[2] we observe constant quantum efficiency for currents greater than 10 A/cm^2.

As the current was increased the half width decreased, at first only slightly, but at currents of 10^4 to 10^5 A/cm^2, the narrowing was striking, as can be seen in Fig. 1.

At high current densities heating of the *p-n* junction, due to its series resistance, causes a shift of the bandgap and, therefore, a shift of the emission line during the duration of the pulse. This shift results in an overestimation of the half-width of the line at currents above 10 A. The line-width values given for currents above 10 A represent only upper limits. In one diode, at the highest currents used, the emission line was resolvable into two lines approximately 6 Å apart and 2 Å wide.

The plausibility of stimulated emission in a *p-n* junction may be appreciated from a simple calculation of the ratio of the number of photons which in the steady state must be present in the crystal to the number of electromagnetic modes within both the crystal and the emission line. If one considers the relationship between the intensity of light emission from the crystal and the density of photons in the crystal, taking into account internal reflection effects, it can be shown that, at a current density of 10^5 A/cm^2 , a quantum efficiency of 0.5, and a line width of 0.02 eV, there are 100 photons per electromagnetic mode. With such a photon population radiative emission would be almost entirely stimulated. Narrowing of the emission line and geometrical mode selection would yield a larger photon population per mode but in a fewer number of modes.

The fact that the quantum efficiency is relatively constant for current densities at which the line width narrows rapidly (it is presumed that the photon occupation number of the reinforced modes increases

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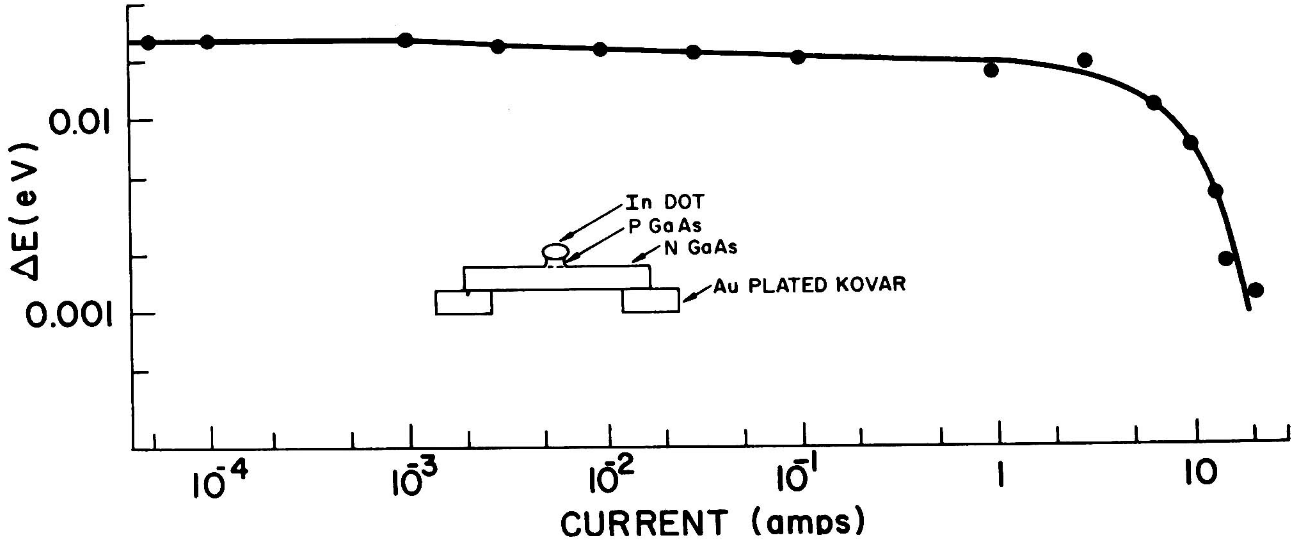

Fig. 1. Full line width at half maximum intensity vs injection current. The area of the diode is 1×10^{-4} cm^2. The inset shows the geometric configuration of the diode.

rapidly) is evidence that the quantum efficiency is close to 100%.

The presence of stimulated emission probably has an effect on the high frequency characteristics of the diodes. Under conditions giving high photon occupation numbers, the response time of the diodes should be even smaller than those already reported.[2]

We are indebted to many of our colleagues at the IBM Research Center for their close cooperation. In particular we thank Drs. R. W. Keyes and R. W. Landauer for stimulating discussions and continuing interest in this work, and Mr. B. Jenkins for technical assistance.

[1] A. L. Schawlow and C. H. Townes, *Phys. Rev.* **112**, 1940 (1958).

[2] A similar structure has been used by R. J. Keyes and T. M. Quist, *Proc. Inst. Radio Engrs.* **50**, 1822 (1962).

[3] J. I. Pankove and M. Massoulie, *Bull. Am. Phys. Soc.* **7**, 88 (1962). J. I. Pankove and J. E. Berkeyheiser, *Proc. Inst. Radio Engrs.* **50**, 1976 (1962).

[4] S. Mayburg, Post deadline paper, Baltimore American Physical Society Meeting, March 1962.

COHERENT LIGHT EMISSION FROM GaAs JUNCTIONS

R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson
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(Received September 24, 1962)

Coherent infrared radiation has been observed from forward biased GaAs *p*-*n* junctions. Evidence for this behavior is based upon the sharply beamed radiation pattern of the emitted light, upon the observation of a threshold current beyond which the intensity of the beam increases abruptly, and upon the pronounced narrowing of the spectral distribution of this beam beyond threshold. The stimulated emission is believed to occur as the result of transitions between states of equal wave number in the conduction and valence bands.

Several requirements must be fulfilled[1] in order that such stimulated emission can be observed: (a) The electron and hole populations within the active region must be large enough that their quasi-Fermi levels are separated by an energy greater than that of the radiation; (b) losses due to absorption by other processes must be small relative to the gain produced by stimulated emission; and (c) the active region must be contained within a cavity having a resonance which falls in the spectral range within which stimulated emission is possible.

In our structure, the necessary population inversion is produced by injection of carriers from the degenerate *n*- and *p*-type end regions of the junction into the transition region. Condition (b) is the most difficult to fulfill, since the stimulated radiation propagates in the plane of the junction where the active region may be only a fraction of a wavelength in thickness and has a wave front which laterally extends many wavelengths into the passive *n*- and *p*-type regions bounding the junction plane. Laser action is favored by the large matrix element for band-to-band radiative recombination compared with that for free carrier absorption in GaAs and by the fact that the energy of the emitted radiation is below the absorption threshold of the degenerate material bounding the junction.

The diodes can be described approximately as cubes 0.4 mm on an edge, the junction lying in a horizontal plane through the center. Current is passed through the junction by means of Ohmic contacts attached to the top and bottom faces. The front and back faces are polished parallel to each other and perpendicular to the plane of the junction, in order to satisfy condition (c) above. Current is applied in the form of pulses of 5 to 20 μsec duration with the diode immersed in liquid nitrogen.

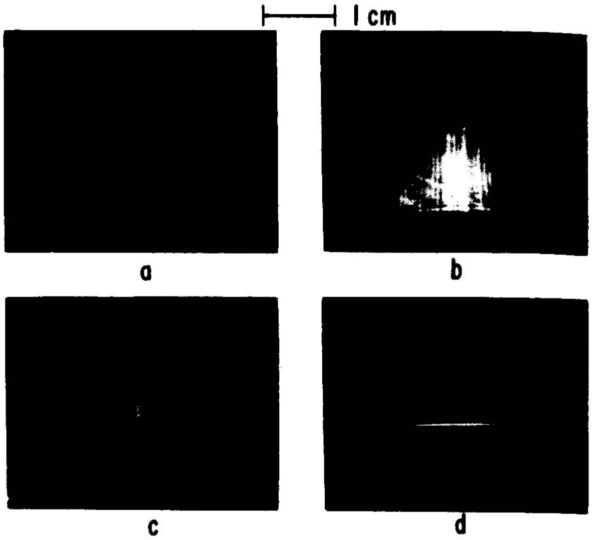

FIG. 1. Radiation patterns observed with image tube a distance *d* from junction. (a) and (b), diode L-69 below and above threshold, $d = 6$ cm. (c) Diode L-69 above threshold, $d = 15$ cm. (d) Diode L-75, $d = 5$ cm.

We have studied the radiation pattern by means of an infrared converter tube which provides an image that can be examined visually or photographically. Examples of such patterns are given in Fig. 1. The first two photographs show the pattern produced by a diode with the current below and above threshold, with the image converter 6 cm from the diode. Figure 1(c) shows the same diode above threshold with the screen 15 cm away, so that the radiation pattern is correspondingly enlarged. In these photographs the horizontal bands result from interference between the light produced at the junction and its image in the metal disc on which the diode was mounted, and their presence does not imply coherence of the source. On the other hand, the vertical bands which appear only in Figs. 1(b) and 1(c) are due to interference between the waves emitted at various points along the edge of the junction at the front face of the cube, and their appearance is evidence that a definite phase relation exists between the light emitted at various points along the junction, i.e., that the light is coherent. The angular separation between the interference maxima is consistent with the dimensions of the junction and the wavelength

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of the radiation. However, the relative intensities of the maxima produced by this and other similarly constructed diodes indicate that the radiation is not produced by the most elementary mode of this type of cavity.

Measurements were made of the light intensity from diode L-70 as a function of junction current at 8420 Å on the axis of the beam. Below 5000 A/cm^2 the light intensity varied linearly with current density. Near 8500 A/cm^2 the intensity increased very rapidly with current, reaching a value about ten times the extrapolated low-current intensity at 20 000 A/cm^2. Such a current threshold is characteristic of the onset of stimulated light emission, and it is significant that the azimuthal interference maxima of Fig. 1 make their appearance at this threshold.

Figure 2 shows the spectral distribution measured with the spectrometer located on the beam axis at several values of current density. Below threshold, the spectral width at half maximum is 125 Å, in agreement with the measurements of Keyes and Quist.[2] As the current is increased through threshold, the spectral width decreases suddenly to 15 Å, in a manner which again is characteristic of the onset of stimulated emission. If this 15Å width is due to a single resonant mode so that the emission is homogeneously broadened by the lifetime of this mode, then the oscillations persist only for a period of 1.6×10^{-12} sec or for a time long enough for the radiation to travel 0.1 mm, which is less than the length of the crystal. However, the broadening may instead be due to oscillations occurring at several unresolved modes during the pulse or to a variation in the wavelength of the resonant mode during a pulse. The instrumental resolution was about 3 Å.

Additional modes appear at longer wavelengths when the current is further increased beyond threshold, as illustrated in Fig. 3. The fact that the additional modes appear at lower energy suggests that the principal dissipative process becomes more effective at longer wavelengths, as would be the case for free carrier absorption. The separation of these additional modes is about three times that calculated on the assumption that each corresponds to one additional half wavelength between the plane surfaces, which were 0.32 mm apart in this diode.

Other junctions have been constructed which ex-

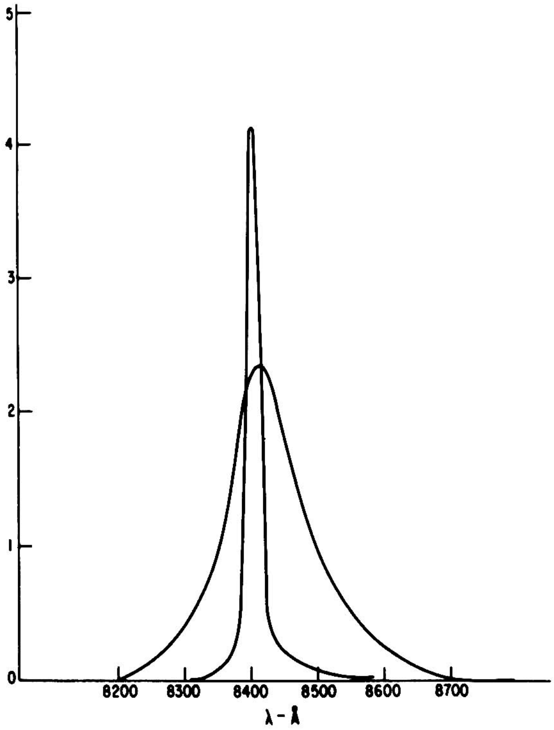

FIG. 2. Spectral distributions from diode L-69 below and above threshold. Different vertical scales.

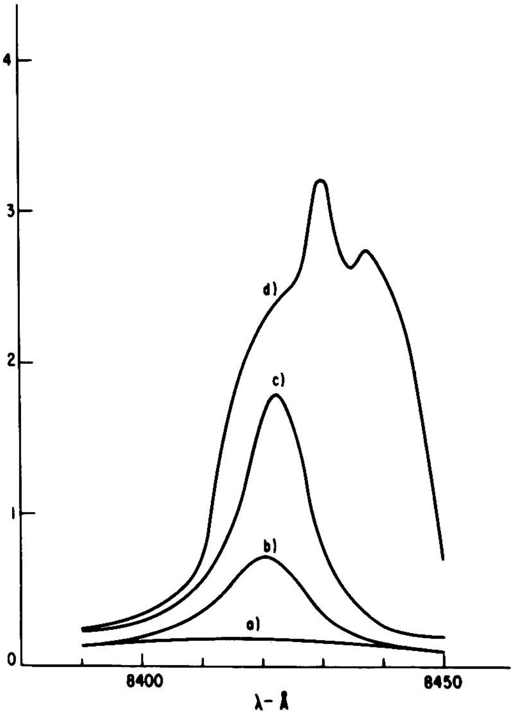

FIG. 3. Spectral distributions of diode L-70 at various currents, same vertical scale for all curves, arbitrary units. (a) 6000 A/cm^2, (b) 8600 A/cm^2, (c) 10 400 A/cm^2, (d) 20 000 A/cm^2.

hibit quite different characteristics. These produce a radiation pattern which is almost uniform in the azimuthal plane, but which is only a few tenths of a degree wide in the vertical plane, as shown in Fig. 1(d). This pattern implies that there is coherence over a distance of the order of 100 μ in the vertical direction but virtually no spatial coherence in the horizontal direction.

While stimulated emission has been observed in many systems, this is the first time that direct conversion of electrical energy to coherent infrared radiation has been achieved in a solid state device. It is also the first example of a laser involving transitions between energy bands rather than localized atomic levels.

---

[1] M. G. A. Bernard and G. Duraffourg, Physica Status Solidi 1, 699 (1961).

[2] R. J. Keyes and T. M. Quist, Proc. Inst. Radio Engrs. 50, 1822 (1962).

COHERENT (VISIBLE) LIGHT EMISSION FROM $Ga(As_{1-x}P_x)$ JUNCTIONS*

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(Received October 17, 1962)

Recently Hall, Fenner, Kingsley, Soltys, and Carlson[1] (HFKSC) reported generation of coherent infrared radiation from forward-biased GaAs *p-n* junctions. We wish to report similar generation of shorter wavelength coherent (visible) radiation from forward-biased $Ga(As_{1-x}P_x)$ *p-n* junctions. As in the experiments reported by Hall and others, evidence for coherent light emission in $Ga(As_{1-x}P_x)$ is based upon the observation of a threshold current beyond which the light intensity increases sharply, upon the pronounced narrowing of the spectral distribution of emitted light beyond threshold, and upon the sharply beamed radiation pattern of the emitted light. Again, as in the case described by HFKSC, the stimulated emission is believed to occur as the result of transitions between states of equal wave number in the conduction and valence bands. It is believed this occurs because of the choice of the ratio of P to As in $Ga(As_{1-x}P_x)$ so that the crystal is a "direct" semiconductor.[2]

In the present case the conditions on (1) junction design and doping, (2) degree of inversion (by injection) of carriers in conduction band and valence band states in the junction transition region, and (3) geometrical relationship of the junction plane to the bounding, parallel "cavity" faces for stimulated emission are as described in ref. 1.

Our $Ga(As_{1-x}P_x)$ diodes are rectangular parallelepipeds or cubes with two opposite, parallel sides carefully polished and with an active (junction) area $\sim 10^{-3}\text{cm}^2$. In each diode a diffused junction lies 10 μ or deeper from one contact surface into the crystal and is perpendicular to the two polished surfaces. Most of our diodes have been fabricated on *n*-type $Ga(As_{1-x}P_x)$, prepared by the halogen vapor transport and synthesis procedure we have previously described.[3] Donor impurity concentrations greater than $10^{18}/\text{cm}^3$ have been employed.

Electrically, the diodes have "clean" V-I characteristics and rise steeply into forward conduction on a scale comparable to that of high quality GaAs *p-n* junctions. As expected, because of the larger (variable) bandgap of $Ga(As_{1-x}P_x)$, the diodes require higher forward voltages than GaAs junctions) [*e.g.*, 1.3 V (diode 28A) as compared to 1.0 V at the "corner" leading to steep current increase]. The overall high quality and efficiency of these junctions is indicated by the fact that in free air (300°K) currents from 20 mA to over 100 mA do not overheat the junctions and are sufficient to produce easily perceptible red light emission.

The evidence for stimulated emission may be conveniently presented by referring to Fig. 1, which represents data taken on diode 28A while it was immersed in liquid nitrogen. Below $\sim 11{,}000$ A/cm^2 the light intensity varied linearly with current (pulsed-current, pulses 1- to 5-μsec long). Above $\sim 11{,}000$ A/cm^2 the light intensity increased sharply with current (super-linear region) and began to assume a narrower pulse width than the somewhat rounded input current pulse. This threshold behavior characterizes the onset of stimulated emission.

As shown by curve (*a*) of Fig. 1 the spectral width below or near threshold (11,000 A/cm^2) was ~ 125 Å. Although it is not shown on Fig. 1, the spectral width at 16,000 A/cm^2 narrowed to ~ 20 Å and, as shown by curve (*b*), narrowed to ~ 12 Å at 19,000 A/cm^2. This, also, is consistent with the onset of stimulated emission. Whereas the GaAs junctions described by Hall and others emitted coherent radiation near 8400 Å, it will be noticed that for diode 28A we have been able to shift the wavelength to a sharply peaked output at 7100 Å.

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