G. Burns
R. A. Laff
S. E. Blum
F. H. Dill, Jr.
M. I. Nathan

Directionality Effects of GaAs Light-Emitting Diodes: Part I

Stimulated emission was recently observed by Nathan et al.[1] in forward-biased GaAs *p-n* junctions.* Part I of the present Letter describes the fabrication and operation of such diodes so that strong directional effects are obtained. In Part II detailed aspects of the directionality above threshold are discussed.[2]

Since, in the injection laser, one is dealing with diodes and electrical injection rather than large homogeneous crystals and optical injection as in the optically pumped laser, the problems are somewhat different, even after a suitable material is found.

The diodes that give typical, good results are made by diffusing Zn into a wafer of perhaps 3×10^{17} cm^{-3} Te- or Si-doped GaAs. The diffusion temperature of $\approx$850°C for 16 hr forms a *p-n* junction $\approx 2\times10^{-3}$ inch below the surface. The diode is then cut to give smooth faces perpendicular to the *p-n* junction plane. One can then obtain cubes, which should lower the threshold because of mode selection,[3] and stimulated emission[1] at lower thresholds has been observed in these units.

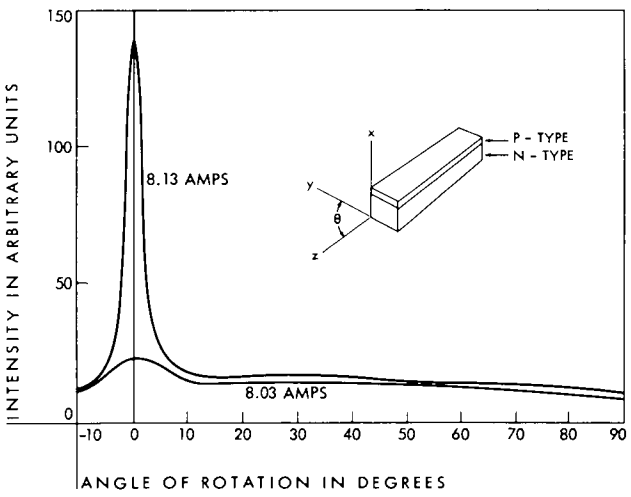
However, the best laser action has been obtained from rectangular parallelepipeds. Typical dimensions are 5×10^{-3} by 50×10^{-3} inch. It is not necessary to coat the small faces of the specimen with any reflecting substance since the high index of refraction of GaAs will cause $\approx 35\%$ reflection of the 8400 A emission.

Using this type of rectangular structure one can, for example, obtain a highly directional beam out of the small area of the rectangular parallelepiped (amplification along the length of the rectangle) at typically 8 amp (area $\approx$ 10^{-3} cm^2) while in the perpendicular direction, line narrowing is not observed until an injection current of typically 18 amp is reached. Thus, as the current is increased above 8 amp, the emitted radiation parallel to the long axis becomes highly superlinear.

Figure 1 shows the angular distribution of emitted radiation just at threshold. The long direction of the rectangular parallelepiped corresponds to 0°. As can be seen the light intensity increases by a factor of more than 12 along the preferred direction for a current change of 0.1 amp. In the junction plane the width of the cone of emitted light is 2.5 degrees, as can be seen in the Figure. Perpendicular to the junction plane the width is about twice as large. At higher currents the modes become more complicated.[2]

Measurements of the current vs total radiation that is emitted in the region of the edge were made on these lasers. The measurements were made by immersing the diodes in a liquid-nitrogen-filled silvered dewar. An S-1 response photomultiplier and a Corning 7-69 filter were placed directly above the dewar and the diode was positioned so that no direct light could reach the photomultiplier. Within experimental accuracy the total light output is linear with current, even though one has strong directionality effects and line narrowing.

Figure 1 **A plot of the intensity of the light emitted in the plane of the junction as a function of angle from the long direction of the rectangle at two currents.**



Acknowledgment

It is a pleasure to acknowledge discussions and help from many of our colleagues. Drs. N. G. Ainslie, J. C. Marinace, and R. F. Rutz have been very generous with their time in helping with materials preparation problems. Stimulating discussions with Drs. W. P. Dumke, R. W. Keyes, G. J. Lasher, P. P. Sorokin and M. J. Stevenson have been very helpful. Also the technical assistance of Miss A. R. Benoric, J. A. Bradley, E. W. Harden and B. A. Jenkins is gratefully acknowledged.

References and footnotes

1. M. I. Nathan, W. P. Dumke, G. Burns, F. H. Dill, Jr., G. J. Lasher, *Appl. Phys. Letters* **1**, 62 (1962).
2. R. A. Laff, W. P. Dumke, F. H. Dill, Jr., and G. Burns, *IBM Journal* (Part II of this Letter).
3. P. P. Sorokin, private communication.

Note added in proof:

* Stimulated emission in GaAs diodes has also been observed by R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, *Phys. Rev. Letters* **9**, 366 (1962).

Received October 29, 1962

R. A. Laff
W. P. Dumke
F. H. Dill, Jr.
G. Burns

Directionality Effects of GaAs Light-Emitting Diodes: Part II

The narrowing of the emission line from GaAs junctions, demonstrating the presence of stimulated emission, has recently been reported.[1] In Part I of this Letter, the fabrication and operation of such diodes in order to obtain strong directional effects is described.[2] Pronounced directional effects in suitable structures showing stimulated emission can be related to standing electromagnetic modes consistent with the geometry of the structure. In Part II we will describe briefly some of the directional effects associated with a rectangular GaAs diode which has a length-to-width ratio of $\approx 10{:}1$ in the plane of the junction.

In these experiments the width of the junction used was $(4.78 \pm 0.05) \times 10^{-3}$ inch, the length 47.0×10^{-3} inch, and the total thickness of the wafer 6.0×10^{-3} inch, about one-third of the thickness being *p*-type and the rest *n*-type. The experiments were carried out with the sample immersed in liquid nitrogen. The diode was driven by current pulses of 100-nsec duration. The directionality of the emitted radiation was observed when the junction was rotated on an accurately calibrated turntable. The radiation was detected with an infrared photomultiplier equipped with a Corning 7-69 filter to pass only wavelengths in the range of the stimulated emission (8400 A). The photomultiplier aperture employed, at a distance of one meter from the junction, yielded an angular resolu-

Figure 1 **Angular dependence of emitted intensity in the junction plane.**