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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).
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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).

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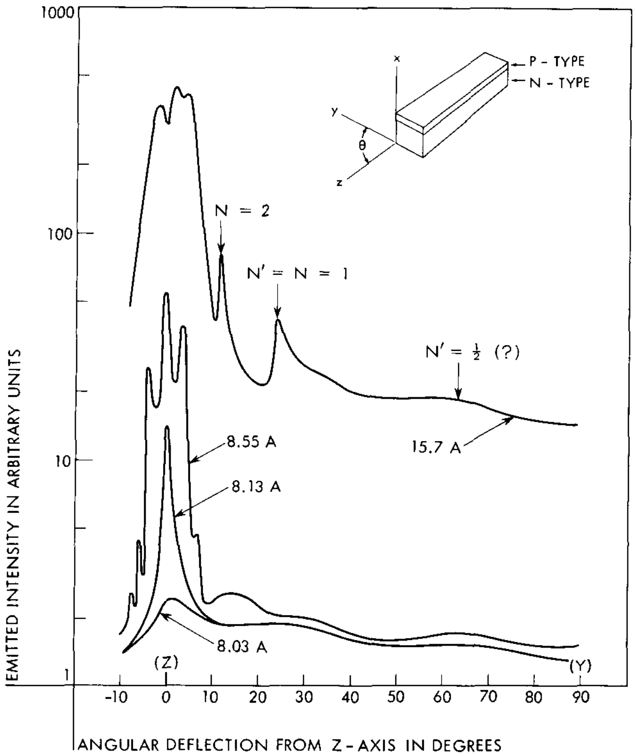
Directionality Effects of GaAs Light-Emitting Diodes: Part II

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 ≈10:1 in the plane of the junction.

In these experiments the width of the junction used was $(4.78\pm0.05)\times10^{-3}$ 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.**



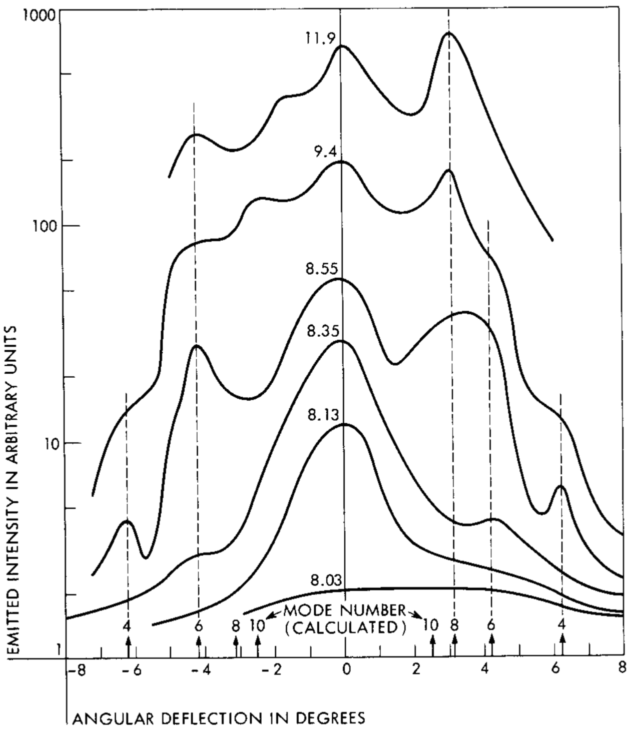


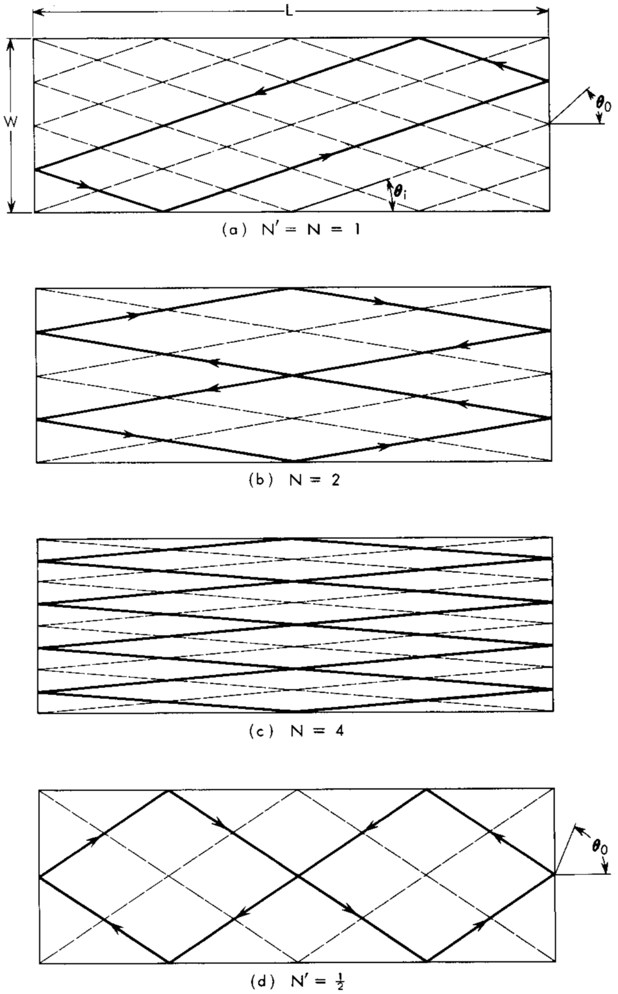
Figure 2 **Detailed structure of emitted intensity near length axis.**

tion of 0.2 degrees.

The threshold for stimulated emission in the long direction of the crystal (z-axis) was approximately 8 amp, corresponding to a current density of 5.5×10^3 amp/cm^2. The threshold is considerably lower than previously reported for etched junctions.[1]

Intensity as a function of angle away from the z-axis in the plane of the junction (y-z plane) is shown in Fig. 1 at various current levels. A pronounced peak appears at 8.13 amp in the z-direction with a total width at half-maximum intensity of 2.5 angular degrees. As the current is increased, several subsidiary peaks appear. The detailed nature of this structure is indicated in Fig. 2 for angles near the z-direction.

Using the known sample geometry and index of refraction ($n = 4.2$) we may correlate the observed positions of intensity peaks with certain simple electromagnetic standing waves in the structure. As an example the peak observed at approximately 25 degrees is believed to originate from the standing wave shown in Fig. 3a. The calculated angle of emission from this mode is $25°15' \pm 30'$. Other modes appearing at smaller angles, corresponding to the several reflections that occur along the length of the sample as the light waves traverse its width, are shown in Figs. 3b and 3c. More complex modes, for which the light waves must traverse the width of the sample several times before repeating the initial path, are not clearly apparent in the data, with perhaps one exception. The low, broad maximum at approximately 60° correlates with the mode shown in Fig. 3d.



(a) N′ = N = 1

(b) N = 2

(c) N = 4

(d) N′ = ½

$$\theta_i = \tan^{-1}(W/NL)$$

$$\sin\theta_0 = n\sin\theta_i$$

$$\theta_0 = \sin^{-1}\left(n\sin\left[\tan^{-1}(W/NL)\right]\right)$$

Figure 3 **Schematic representation of some simple geometric standing modes with easy closure.**

Two separate polarization effects are observed to be characteristic of the on-axis radiation and of that present in the major side peaks, e.g., at approximately 4° off-axis. The threshold for stimulated emission in this direction is slightly higher than that for on-axis, i.e., 8.35 amps. Close to threshold, both the on-axis radiation and that at 4° are highly polarized with the electric vector perpendicular to the plane of the junction (x-direction). With increasing current, the on-axis radiation becomes less polarized, but the radiation at 4° remains highly polarized out to the maximum current of measurement. This is consistent with the interpretation that the off-axis intensity peaks correspond to internally reflected standing modes, which should become polarized because of internal reflections. We do not at present understand the polarization properties of the on-axis radiation. The angular distribution with respect to the z-axis in the plane perpendicular to the junction (z-x plane) is qualitatively similar in width to the angular distribution in the plane of the junction. However, no detailed fit with the observed structure was attempted since the y-z surfaces of the junction are not plane-parallel surfaces of high reflectivity.

More detailed measurements of directionality and polarization are currently under way on similar structures. However, we believe that the data and our interpretation offer reasonable evidence for the existence of definite geometrical modes in GaAs junctions exhibiting stimulated emission.

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2. G. Burns, R. A. Laff, S. E. Blum, F. H. Dill, Jr., and M. I. Nathan, *IBM Journal* (Part I of this Letter).

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