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Room-Temperature Stimulated Emission

In the recent papers by Nathan et al.,[1] and Hall et al.,[2] stimulated emission was reported in forward-biased GaAs *p-n* junctions at 77°K. Directionality effects[3,4] in these injection lasers have also been discussed. The theoretical groundwork for these measurements has been discussed by several authors[5–7]. In this Letter line narrowing and directionality at room temperature in these diodes are reported.

At 25°C the emission from forward-biased *p-n* GaAs diodes made by diffusing Zn into Te-doped GaAs occurs at 9000 A. At 77°K emission has been observed[8,9] at 8400 A. The emission at room temperature undoubtedly involves the acceptor center, as has been shown[10] at 77°K. In the diodes studied here, typical observed line widths at room temperature are 250A (0.036 ev) at low currents. This is slightly narrower than observed by other authors[8,9] but is still in basic agreement. Under pulsed operation the room-temperature emission of some of these diodes has been observed to narrow. Emission from some diodes has been observed to narrow to as little as 1.5 A($\approx$ KT/100). The threshold for stimulated emission in good units is approximately ten times larger at room temperature than at 77°K.

Figure 1 shows the line width vs current for a room-temperature lasing diode. The upper curve corresponds to observations perpendicular to the long axis of the rectangular parallelepiped[3,4]. The data for the lower curve is taken looking parallel to the long axis. As can be seen the threshold parallel to the axis is lower. Thus, at a given current the emission in the parallel direction is very much narrower and more intense than in the perpendicular direction.

Figure 2 shows the emission parallel and perpendicular to the axis of the rectangular parallelepiped diode at several different currents and at low resolution. Both the narrowing of the emission line and the anisotropy of the narrowing can be seen.

In Fig. (3) careful measurements of the emission along the long axis of the parallelepiped is shown with higher resolution ($\approx$ 1/2 A) at threshold (1.0 $\times$ 10^5 amp/cm^2) and slightly above threshold (1.1 $\times$ 10^5 amp/cm^2). One observes a spike phenomenon[1] similar to the observations at 77°K. The sharper spike pictured is 1.5 A wide. The intensity in the wings of the line, which is linear with current below threshold, becomes very sublinear above threshold.

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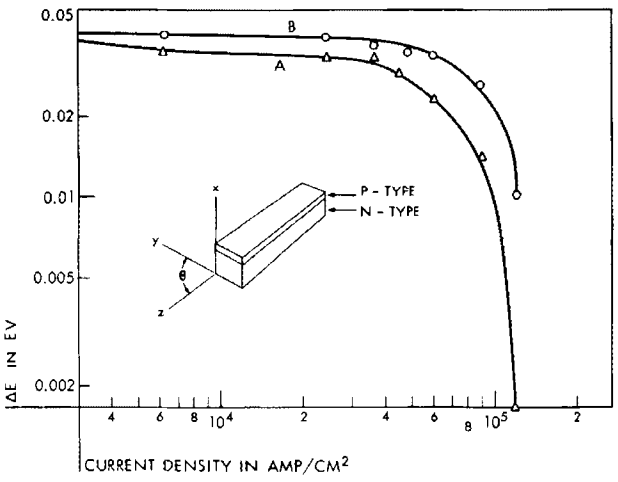
Figure 1 **Full line width at half-maximum intensity vs injection current at 25°C.**
The upper curve corresponds to emission in the y-direction. The lower curve corresponds to emission in the z-direction.



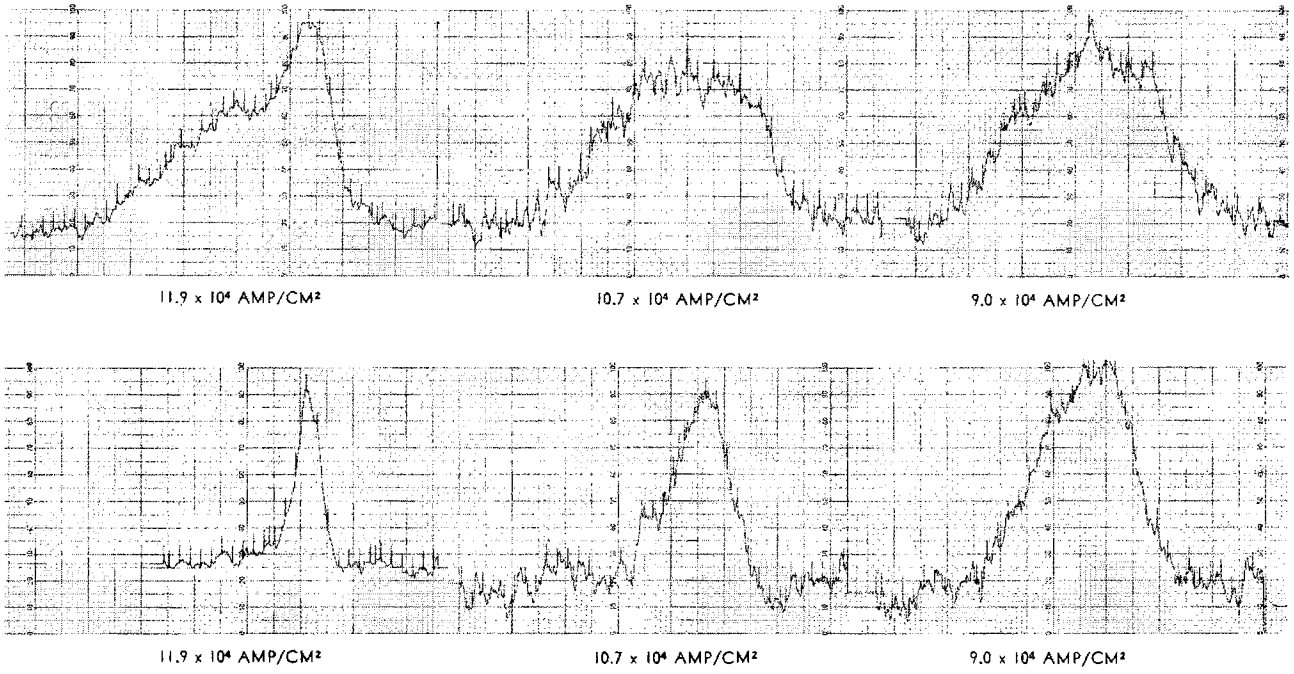


Figure 2 **Radiation intensity as a function of wavelength.**
The diode is being pulsed at the current densities shown. Pulse duration is 60 × 10^{-9} sec; and the pulse rate, 35 /sec. The upper set of curves corresponds to observations perpendicular to the axis and the lower set parallel to the axis. All the measurements are at 25°C. Appropriate circuitry is used so that the results can be made to appear on a chart recorder, but this makes the result slightly nonlinear at low intensities. The emissions actually have a longer tail than indicated on the chart. (The markers occur every 11.0 A, with an extra one appearing every 10 markers.)

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References

1. M. I. Nathan, W. P. Dumke, G. Burns, F. H. Dill, Jr., and G. J. Lasher, *Appl. Phys. Letters* **1**, 62 (1962).
2. R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys and R. O. Carlson, *Phys. Rev. Letters* **9**, 366 (1962).
3. G. Burns, R. A. Laff, S. E. Blum, F. H. Dill, Jr., and M. I. Nathan, *IBM Journal*, this issue, p. 62.
4. R. A. Laff, W. P. Dumke, F. H. Dill, Jr., and G. Burns, *IBM Journal*, this issue,p. 63.
5. M. G. A. Bernard and G. Duraffourg, *Physica Status Solidi* **1**, 699 (1961).
6. W. P. Dumke, *Phys. Rev.* **127**, 1559 (1962).
7. G. J. Lasher, *IBM Journal*, this issue, p. 58.
8. 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).
9. R. J. Keyes and T. M. Quist, *Proc. Inst. Radio Engrs.* **50**, 1822 (1962).
10. M. I. Nathan and G. Burns, to be published in *Applied Physics Letters.*

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Figure 3 **The emission intensity vs wavelength at 25°C.**
The emission is shown for two currents just at threshold and slightly above threshold (34 and 37 amp respectively, the area of the diode is 3.3 × 10^{-4}cm²). The emission is observed parallel to the long axis of the diode. The data presented in this Figure, in contrast to Fig. 2, is a true representation in the wings as well as the intense spikes.