

M. J. Stevenson *

J. D. Axe

J. R. Lankard

Line Widths and Pressure Shifts in Mode Structure of Stimulated Emission from GaAs Junctions

Stimulated emission from forward biased *p-n* GaAs junctions has been reported by several laboratories.^{1,2} Most of the reported spectroscopic measurements have been made under medium resolution. This Communication reports high-resolution measurements of the line width as well as the dependence of the GaAs stimulated emission characteristics on hydrostatic pressure.

Measurements were performed on a Jarrell-Ash 1 meter Ebert spectrometer equipped with a 7500 lpi Harrison grating operated in seventh order. At 8400 Å the maximum obtainable resolution was 0.05 Å, the limit being set by the minimum usable slit widths compatible with an acceptable signal-to-noise ratio. The diode structures used were rectangular slabs about 400 μ long, 100 μ wide and 100 μ thick. The thickness of the *p*-type Zn-diffused region was about one-third of the slab thickness. The end faces of the diodes were made flat and parallel by cleaving. The diode structures were soldered to gold-plated kovar tabs.

All of the measurements were performed at liquid nitrogen temperatures. The diodes were mounted in a stainless steel pressure bomb equipped with a small quartz window. The bomb was in turn immersed in a liquid nitrogen dewar. Pressures up to 150 kg/cm² were applied by pressurized nitrogen gas. Current densities of from 5,000 to 25,000 amps/cm² were applied in 100 nsec pulses at repetition rates of from 50 to 300 pulses/sec.

Linewidth measurements

The diodes used in these experiments were fabricated before the factors influencing mode selection were, to a large extent, controllable. As a result the mode patterns and widths of the stimulated emission lines varied greatly from diode to diode. However, in several units the line widths at threshold of oscillation were less than 0.2 Å, and the narrowest observed halfwidth at half-power points was 0.05 Å, the energy-limited resolving power of the instrument. The actual linewidth at 77°K may thus have been even smaller.

Pressure studies

Two distinct pressure-induced phenomena have been observed in the stimulated emission of a GaAs diode. All of the well-resolved modes shift identically to higher energy with increasing pressure at a rate of 3.5×10^{-6} eV/kg/cm² (-0.0020 Å/kg/cm²). The only clearly observed deviations from linearity were slight hysteresis effects during the first pressure cycle. The relative intensity of radiation in each mode was also reversibly affected. Modes easily distinguished at ambient pressure diminished in intensity, new modes appeared, passed through maximum intensity, and then in turn disappeared. The results of the measurements of the pressure dependence of the mode pattern well above threshold are shown in Fig. 1.

The oscillation frequencies of the GaAs diodes depend upon three major factors: the dimensions of the laser cavity, its index of refraction, and the envelope of the spontaneous emission band. All of these factors are influenced by pressure. The observed pressure shift of the individual modes should be governed by pressure-induced changes in the optical dimensions of the cavity. The wavelength in vacuum of a particular mode may be written as $\lambda = \text{constant} \cdot n \cdot L$, where n is the index of refraction of GaAs and L is some characteristic (but unspecified) cavity dimension. Since the index of refraction is also wavelength dependent, the rate of change of the mode wavelength is given by

$$\frac{1}{\lambda} \frac{d\lambda}{dp} = -\frac{1}{E} \frac{dE}{dp} = \frac{\frac{1}{L} \left(\frac{dL}{dp} \right) + \frac{1}{n} \left(\frac{dn}{dp} \right)}{\left[1 - \frac{\lambda}{n} \left(\frac{dn}{d\lambda} \right) \right]}. \quad (1)$$

All of the quantities of the right side of Eq. (1) can be evaluated from independent measurements,³⁻⁵ with the exception of $(dn/dp)_\lambda$. The value of $(1/n)(dn/dp)_\lambda$ necessary to give the observed mode pressure dependence is -3.1×10^{-6} /kg/cm², which would make the change of index of refraction by far the dominant effect. Semiquantitative calculations of $(dn/dp)_\lambda$ show that values of this order of magnitude are indeed to be expected.⁶ (This treatment

* Now with Quantum Science Corporation, New York, N. Y.

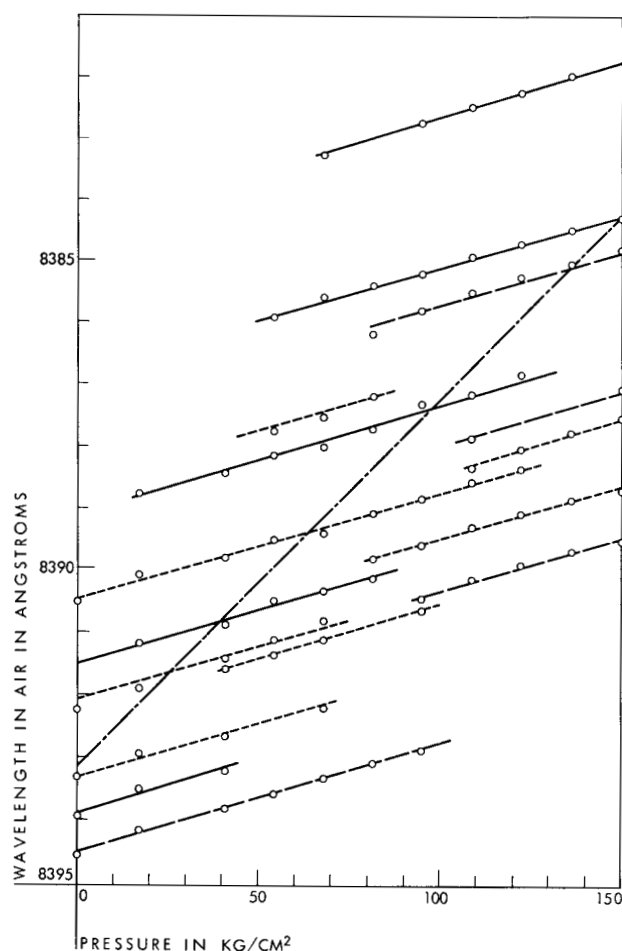


Figure 1 Variation of stimulated emission frequency with hydrostatic pressure.

As the pressure on the diode is increased, the stimulated emission shifts to shorter wavelength. The lines drawn through the experimental points have identical slopes and show the pressure variation of the individual modes. Two distinct progressions of modes separated by a constant interval (2.44 Å) were noted. These mode progressions are connected by the solid and long-dashed lines, respectively. The short-dashed lines represent modes showing no obvious regularities in their wavelength spacing. The intensities of the laser emission lines are strongest within the center portions of their observable range. The chain line of greater slope shows for comparison the magnitude of the rate of change of the spontaneous emission envelope with pressure, (dE_g/dp) [from Ref. 6].

neglects the possible constraints imposed by the metal tab to which the diodes were attached. Several diodes specially fabricated to eliminate this constraint did not produce sufficient light to be studied.)

In addition, the wavelength of the spontaneous recombination radiation itself decreases with increasing pressure at a rate of 12×10^{-6} eV/kg/cm², more than three times greater than that of the individual modes.⁷ It is therefore evident that over a larger pressure range the frequencies of individual modes begin to lag behind the spontaneous emission, causing the intensity of the radiation in the modes to decrease to the point where the modes drop below threshold and disappear. Concurrently the new, more favored modes appear.

Mode shifting and mode jumping have also been observed in this laboratory in a study of the temperature dependence of stimulated emission of GaAs. This behavior has been explained by quite analogous arguments.⁸

Acknowledgments

It is a pleasure to acknowledge the interest and help of our colleagues in this laboratory, in particular M. I. Nathan, P. P. Sorokin, G. Burns, and W. V. Smith. We are especially indebted to F. H. Dill and R. Rutz for supplying us with the diodes, and M. Okrasinski for machine work, without which these measurements would not have been possible.

References and footnotes

1. Nathan, Dumke, Burns, Dill and Lasher, *Appl. Phys. Letters* **1**, 62 (1962); Hall, Fenner, Kingsley, Soltys and Carlson, *Phys. Rev. Letters* **9**, 366 (1962); Quist, Rediker, Keyes, Krag, Lax, McWhorter and Zeigler, *Appl. Phys. Letters* **1**, 91 (1962).
2. Holonyak and Bevacqua, *Appl. Phys. Letters* **1**, 82 (1962).
3. The compressibility at 77°K, $1/L \, dL/dp = -0.43 \times 10^{-6}$ kg/cm² is from bulk modulus measurements of C. W. Garland and K. C. Park, *J. Appl. Phys.* **33**, 759 (1962).
4. D. T. F. Marple finds at 77°K $n = 3.58$. (Unpublished measurement. Quoted by J. D. Kingsley and G. E. Fenner, *Bull. Am. Phys. Soc.* **8**, 87 (1963).)
5. The value $[1 - \lambda/n \, dn/d\lambda] = 1.5$ can be obtained from mode separations reported in Ref. 4.
6. We are indebted to G. J. Lasher for first pointing out to us the possible importance of the pressure dependence of the index of refraction, and more especially to F. Stern for communicating to us the results of his calculations confirming the essential correctness of the above mechanism.
7. W. Paul, *J. Appl. Phys.* **32**, 2082 (1961).
8. G. Burns and M. I. Nathan, *Proc. IEE*, to be published.

Received February 11, 1963