ion (and annihilation) conditions and on the external ircuit connections; no wholly stationary results were ound beyond limiting. Increasing the random-to-drift elocity ratio at the input destroys the repetitive nature f the oscillation and reduces the amplitude of the uctuations; further study is needed to see if the fluctua- ons were correlated with the random input and to see ow much increase in stability is gained by increasing e random content of the input.

The start oscillation conditions, from perturbation nalyses, indicate a weak start with no oscillation. However, the energy behavior, calculated from total quanti- es, indicates a violent start, as does occur. The large gnal behavior of W, W_E, W_K and their time averages eeds to be developed further, in particular, to be eneralized to other models to get the start- and stop- cillation conditions.

The analysis of stability in one-dimensional (infinitely road) electron diodes is now made fairly complete. The two-dimensional (finite diameter stream) diode is shown to behave in a similar manner, but this study is not as exhaustive. The results are useful in themselves with applications to diode and drift-tube stability and to noise smoothing in electron guns and to oscillations in thermionic converters as given in Ref. 1. The results obtained are clues of what to compute and what to look for in more complex configurations.

The experimental observations by ourselves and others are only in partial agreement with these calculations. There is need for extending the analysis to include more effects as well as for improving the understanding of the experiments in order to obtain closer agreement.

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Effect of Hydrostatic Pressure on the Emission from Gallium Arsenide Lasers

G. E. FENNER

General Electric Research Laboratory, Schenectady, New York

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The pressure shift of both the coherent and the incoherent emission of GaAs junction lasers has been measured at about 200°K. The peak of the spontaneous emission shifts by $+1.09\times10^{-5}$ eV/atm, which is in agreement with the pressure coefficient of the band gap in GaAs determined by experiments based on the change of resistance under pressure. The shift of the coherent modes is much smaller, namely, $+2.96\times10^{-6}$ eV/atm. The effect of the compressibility on the latter shift is shown to be negligible. It is concluded from considerations of a simple model that the shift of the coherent radiation is primarily due to a change of the dielectric constant with pressure.

THE recent achievement of coherent light emission from forwardly biased GaAs junctions has pro- ed a tool for more accurate measurements of certain ic parameters of semiconductors. This paper reports e results of hydrostatic pressure experiments on the rent as well as the incoherent output of GaAs lasers 00°K. Like the more familiar types of lasers the tion device consists of two basic ingredients: a n in k space with inverted population where taneous and stimulated emission can occur and a on in physical space forming an optical resonator to ain prolonged oscillations. The first is determined the band structure of the material, whereas the nd depends on the physical dimensions and the tric constant of the medium. Pressure affects these erties differently, and therefore we discuss each of in turn.

a junction laser the population inversion is ved by the injection of a large number of both types of carriers into the junction separating n- and p-type material, where electrons and holes can recombine and emit photons. The exact nature of the process is still subject to speculation. It may involve either conduction band-to-valence band transitions or transitions involving discrete impurity levels close to either of the band edges. One might hope to distinguish between some of the transitions by the difference in effect pressure might have on the energy states involved. The energy of the emitted radiation is smaller than the gap energy by about 0.04 eV. Therefore, only shallow impurity states could possibly be involved in the emission process. One can estimate the effect of pressure on such a state by adopting a hydrogenic model for the impurity. Assuming the change of the ionization energy to be due to the change of the effective mass and the dielectric constant, the estimated shift of the level with respect to the band edge is about 5% for the maximum pressure of 2000 atm employed in our experiments. The experi-

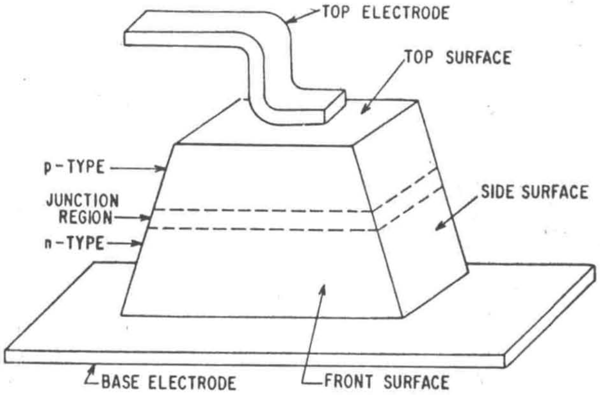

FIG. 1. Laser diode geometry.

mentally determined pressure shifts of similar levels in Si[1] are in agreement with this estimate. While this expected change does fall outside of our experimental uncertainty, the pressure shift of the band gap itself is not known nearly well enough to show up differences of that magnitude. Even if the shift were known more accurately, the concept of a discrete level would be inconsistent with the large impurity concentrations found in our diodes. For these reasons it seems highly improbable that the results of our measurements could be used to identify one of the possible recombination processes.

Unlike some lasers, the crystal itself forms the optical resonator in the junction laser. In our experiments two opposite faces of the crystal are polished parallel to one another as shown in Fig. 1. Because of the large stimulated emission per unit length of active region (region with inverted population) and the large dielectric constant of GaAs, no external reflecting surfaces are required.

The frequencies of the normal modes set up between two parallel reflecting surfaces are given by

$$\nu_{\mathrm{res}}=c/n\lambda_{\mathrm{res}}=cs/2ln, \tag{1}$$

where c is the velocity of light, l the distance between surfaces, n index of refraction, and s the mode number (an integer in the order of 2000).

The application of pressure on a resonator supporting these modes leads to a change in its physical size due to the compressibility of the solid as well as to a change in the dielectric constant.

EXPERIMENTAL DETAILS

The diodes used in our experiments are nearly cubic structures (Fig. 1) with the parallel planes separated by about 4×10^{-3} cm. The junctions are formed by diffusing Zn into n-type wafers with donor concentrations of about 1.5×10^{18} per cc. The acceptor concentrations are several times 10^{19} per cc. The diodes were mounted in an optical pressure cell and the output was measured through a Jarrell–Ash monochrometer with a resolution of 0.3 Å and an accuracy of about 1 Å. The detector was a cooled photomultiplier with a S 1 photoemissive surface.

The pressure fluid used was n-pentane and the cell was cooled by dry ice. The diode temperature was monitored by a cupron copper thermocouple. The shift of the peak of the incoherent emission was found by operating at current levels just below threshold. In order to get an accurate picture of the mode shift of the coherent radiation the diode was operated just at threshold so that several modes were visible. A typical recorder pattern is shown in Fig. 2. Since there is an appreciable amount of thermal tuning during the current pulse, especially at these high current densities (30 000 A/cm^2), the photomultiplier output was sampled using the gate of a Tektronix sampling scope.

In order to follow each mode unambiguously the pressure increments were made as small as possible: typically a few atmospheres. Because a temperature change of 1°K shifts the modes as much as a pressure change of about 50 atm, the measurements in small pressure increments were used only to identify modes, bracket the errors and watch for unexpected developments. Even then a particular mode could be followed for only 250–300 atm, so that the temperature of the sample had to be kept constant to about $\frac{1}{10}$°K to keep errors within reasonable limits. The maximum pressure applied to the diodes was 2000 atm. The pressure was measured with a gauge from American Instrument Company with an accuracy of $\frac{1}{2}$°.

RESULTS

For the peak of the incoherent radiation we find a shift of

$$\Delta\lambda/p\lambda=-7.6\times10^{-6}\ \mathrm{atm}^{-1}$$

giving for the emitted radiation

$$h\nu(\mathrm{eV})=1.43+(1.09\pm0.04)\times10^{-5}\ p(\mathrm{atm}).$$

The evaluation of the data for the coherent radiation was somewhat complicated by the fact that the diode structure is not ideal and that therefore the mode separation is not the same for all modes. Also, differential strains exist in the crystal which are modified under the application of pressure. A least-square analysis of the pressure dependence of about 40 different modes leads to an average mode shift of[2]

$$\Delta\lambda_{\mathrm{res}}/p\lambda_{\mathrm{res}}=(-2.07\pm0.05)\times10^{-6}\ (\mathrm{atm})^{-1}$$

or in terms of energy

$$\Delta h\nu/\Delta p=2.96\times10^{-6}\ \mathrm{eV/atm}$$

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[1] M. G. Holland and W. Paul, Phys. Rev. 128, 30 (1962).

[2] This is in general agreement with measurements reported in Refs. 3 and 4.

[3] J. Feinleib, S. Groves, W. Paul, and R. Zallen, Bull. Am. Phys. Soc. 8, 201 (1963).

[4] M. J. Stevenson, J. D. Axe, and J. R. Lankard, Bull. Am. Phys. Soc. 8, 310 (1963).

showing that the incoherent radiation shifts more than $3\frac{1}{2}$ times as fast as the individual modes. This is the reason for the earlier statement that the modes could only be followed over a limited pressure range.

DISCUSSION

The results for the pressure dependence of the peak of the incoherent radiation are in agreement with the published values for the pressure shift of the energy gap. The results of experiments to determine this latter shift differ appreciably, however,[5] so that no information can be gained by a direct comparison of the two experiments. If the assumption is made that there is a one-to-one correspondence between the shift of the peak of the radiation and the gap itself, then the pressure coefficient derived from our experiments falls near the mean of the published values.

In the case of the coherent emission we find for the resonance frequency of a mode $\nu_{\mathrm{res}}(l,n)$

$$\frac{d\nu_{\mathrm{res}}}{dp}=\frac{cs}{2}\left[-\frac{1}{l^2n}\frac{dl}{dp}-\frac{1}{ln^2}\frac{dn}{dp}\right].$$

Remembering that the index of refraction n is a function both of pressure and of frequency we find for the relative shift of a particular mode

$$\frac{1}{\nu_{\mathrm{res}}}\frac{d\nu_{\mathrm{res}}}{dp}=\frac{1}{\lambda_{\mathrm{res}}}\frac{d\lambda_{\mathrm{res}}}{dp}$$

$$=\frac{-\frac{1}{3}n\kappa}{[n+\nu_{\mathrm{res}}(\partial n/\partial\nu_{\mathrm{res}})]}+\frac{\partial n/\partial p}{[n+\nu_{\mathrm{res}}(\partial n/\partial\nu_{\mathrm{res}})]}. \qquad (2)$$

On substituting the values $\kappa=13.2\times10^{-7}\,\mathrm{atm}^{-1}$ for GaAs,[6] $n=3.59$, and $n+\nu(\partial n/\partial\nu)=5.2$ from Marple's measurements,[7] the first term on the right of Eq. (2) turns out to be

$$-\tfrac{1}{3}\kappa n/[n+\nu_{\mathrm{res}}(\partial n/\partial\nu_{\mathrm{res}})]=-3.04\times10^{-7}\,\mathrm{atm}^{-1}.$$

Comparing this with the measured value, it becomes apparent that the major portion of the shift is due to the change in dielectric constant with pressure.

We employ a simple model to show that this result is reasonable. Since the photon frequency ν is close to that of the [000] band gap ν_g, we make the assumption that the dispersion of the index is determined largely by this gap and is a function only of $\nu-\nu_g$. This is in agreement with the analysis by Stern,[8] who predicts a sharp maximum for the index at the band edge of the [000] minimum. Further, we assume that the dispersion as a function of $\nu-\nu_g$ does not vary appreciably with pressure. This implies that $\partial n/\partial p$ at a given frequency ν is determined solely by the variation of ν_g if the effect of pressure on the dc dielectric constant and the interband transitions at higher energies is neglected. By translating the n versus frequency curve rigidly along the ν axis by an amount determined by the known pressure shift of the [000] gap[5] we therefore estimate:

$$\partial n/\partial p/[n+\nu(\partial n/\partial\nu)]=-2\times10^{-6}\,\mathrm{atm}^{-1}.$$

It should be noted that the rigid shift with pressure assumed here for the dispersion in the vicinity of ν_g appears also to be characteristic of the corresponding variation with temperature, as shown by Marple's data.[7]

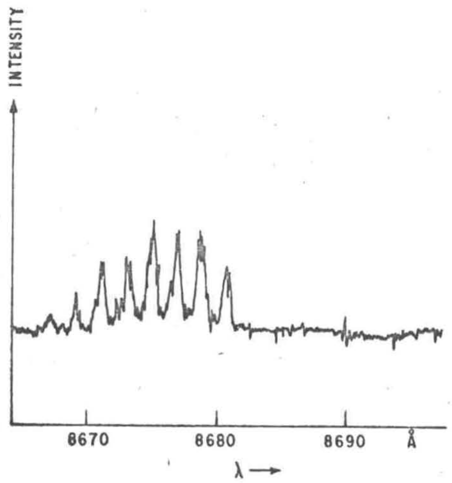

FIG. 2. Intensity vs wavelength at T=190°K and 136 atm pressure (diode L351).

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[5] W. Paul, J. Appl. Phys. **32**, 2082 (1961).

[6] T. B. Bateman, H. J. McSkimin, and J. M. Whelan, J. Appl. Phys. **30**, 544 (1959).

[7] D. T. F. Marple (private communication).

[8] F. Stern, Bull. Am. Phys. Soc. **8**, 201 (1963).