doubled.

(B) No transport current is present initially. Layers 1 and 3 fill and share the sheet equally. Introducing a transport current displaces circulating currents from the middle sheet and also disturbs the initial state in the remaining volume according to the processes discussed above in (i).

Applying this artificial model to the operations of Fig. 2(a) for the paramagnetic and diamagnetic cases leads to complete agreement with the empirical observations presented above. Pursuing this simple model leads to the expectation that after the quenching of the magnetization produced by one cycle of current, additional cycling (magnitude remaining constant) will not disturb the magnetization further, in agreement with our measurements within experimental accuracy.

Although we have assumed, for simplicity, that the transport and circulating currents occupy physically separate regions, we may expect that in a real superconductor, where both types of currents are superimposed and the situation is more complicated, the phenomena considered above still occur and account for our observations. As the transport current is changed, the total current distribution and the flux configuration in the specimen is modified in such a way that the local total current density tends to rise above critical in some elements of volume while it becomes subcritical in others of equivalent effective volume. Our discussion indicates that the field associated with the transport current as well as the transport current itself can influence the magnetization. Our results confirm and extend the Bean model of a hard superconductor and indicate that the critical magnetization curve (diamagnetic and paramagnetic) can be obtained from the I_c vs H curve and vice versa.

Below ≈3 kG, the behavior of the paramagnetic magnetization conforms to the above discussion until "anomalous" resistive transitions at critical currents I_c' (curve B of Fig. 1) perturb the measurements. This phenomenon is tentatively attributed to the sudden local onset of an intermediate state which disrupts the critical state, since over part of the cross section of the wire the local field becomes $H_a - 2I_c'/10r \approx H_{FP}$. At the same H_a and I_c' on the initial magnetization curve, the sample is not in a critical state and the appearance of an intermediate state is not "catastrophic."

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[1]While this work was in progress, Dr. D. Bruce Montgomery communicated to the author independent observation of this phenomenon.

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OSCILLATIONS IN GaAs SPONTANEOUS EMISSION IN FABRY-PEROT CAVITIES

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In injection lasers,[1-3] just below the threshold for single-mode operation, equally spaced lines in the spectrum have been observed. The lines are due to stimulated emission in low-loss modes of the Fabry-Perot cavity and they have been discussed by several workers.[4-6] In this Letter we report the observation of oscillations in the spectra of some GaAs injection lasers a factor of more than 40 at 2°K and 500 at 77°K below the threshold current for single-mode operation. As threshold is approached, these oscillations merge continuously with the equally spaced lines discussed above. However, they do not result from stimulated emission but arise from multiple reflections of the spontaneous emission between the ends of the Fabry-Perot cavity. This phenomenon has been theoretically discussed previously[7,8] but not observed. From the study of these oscillations as a function of current it is possible to measure, among other things, the internal loss of the laser and the variation of index of refraction in the region of the absorption edge.

The lasers studied were made by diffusing Zn into Te-doped GaAs and had cleaved ends and

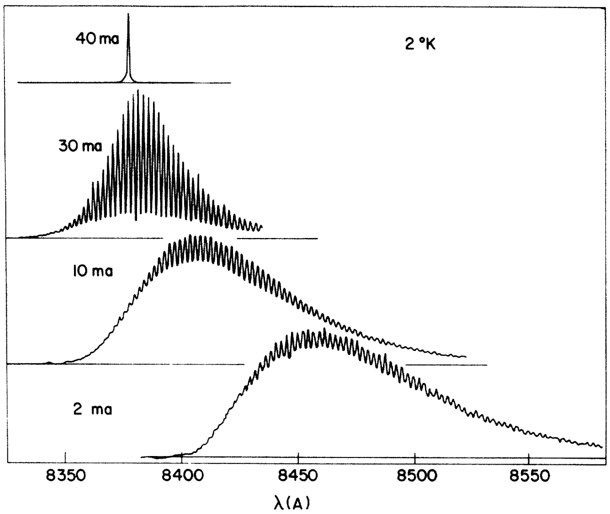

FIG. 1. Spectra of laser 17-71-17. 2 mA, slits = 50 μ, gain = 1; 10 mA, slits = 50 μ, gain = 0.05; 30 mA, slits = 30 μ, gain = 0.02; 40 mA, slits = 2 μ, gain = 0.075. Dispersion of spectrometer = 27 Å/mm. Length of cavity = 0.032 cm. Junction area 1.6×10^{-4} cm^2. The laser is running continuously.

sawed sides. The spectra at several currents observed along the axis of a typical laser with a substrate doping of 9×10^{17} cm^{-3} are shown in Fig. 1. As can be seen in this unit the oscillations are clearly visible at 2 mA. Actually they can be seen down to 1 mA (=6 A/cm^2). Below this current the rapid decrease of quantum efficiency prevents observation. Although it is not shown, the oscillations are visible from the peak of the line to more than 400 Å at 2°K and 600 Å at 77°K on the long-wavelength side of the line. In Fig. 1 the shape of the oscillations was instrument limited. Careful measurements were made at higher resolution and slower scan. The visibility ($v = I_{max}/I_{min}$, where I_{max} and I_{min} are the maximum and minimum intensities) at 8460 Å, the peak of the spontaneous emission line at 2 mA, is shown as a function of current in Fig. 2. The visibility is independent of current for small currents, then increases until threshold for single-mode operation, $I = 45$ mA, is reached. There was a slight increase in the threshold current between the runs for Fig. 1 and Fig. 2. The angular aperture for these measurements was 2° in the plane of the junction by 5° in the perpendicular plane. Decrease of the aperture to approximately 1° in either plane caused at most a 5% increase in v at 10 mA. The oscillations disappeared if the laser was rotated off axis by about 10°.

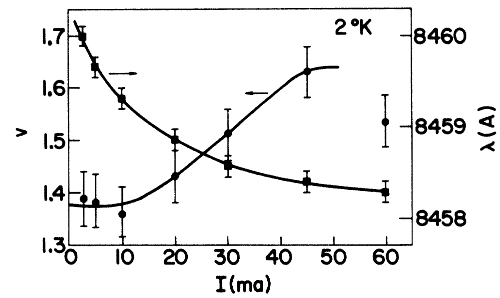

FIG. 2. Laser 17-71-17. Visibility (circles) and wavelength (squares) of a peak vs current. (Measurements made at 30-μ slits at low currents and 17-μ and 30-μ slits at high currents. Decrease of slits caused 10% increase in v. The values of v at low current have been increased by this factor.) The decrease of v between 45 mA and 60 mA is probably due to scattered light in the spectrometer.

The oscillations are axial modes of the Fabry-Perot cavity whose periodicity is determined by

$$m\lambda = 2nl, \qquad (1)$$

where m = mode number, λ = wavelength, n = index of refraction, and l = cavity length. The fact that the oscillations are observed so far below threshold and that their visibility is independent of current for small currents show that they do not result from stimulated emission. Moreover, a simple calculation shows the density of photons per electromagnetic mode is small compared to unity for 2 mA through the diode.

It has been shown that such oscillations are expected from a spontaneously emitted medium in a Fabry-Perot etalon.[7,8] The visibility, v, has been shown to be

$$v = (1 + 4Re^{-2\alpha l})/(1 - Re^{-2\alpha l}) \qquad (2)$$

for small acceptance angle, where R is the reflectivity and α is the effective loss constant for the wave and is a function of current and wavelength. The laser is not a true Fabry-Perot etalon because the transverse dimensions of the active region are small compared to the length of the cavity. However, since absorption in the inactive region will reduce the light emitted by some off-axis modes, this serves to decrease the effect of a finite acceptance angle in lowering the visibility of the oscillations.[9]

Using Eq. (2), the data of Fig. 2, and $R = 0.3$, we find $\alpha = 25$ cm^{-1} for current $i < 10$ mA and $\alpha = 13$ cm^{-1} for $i = 40$ mA at 8460 Å. At shorter wavelength α becomes negative at high current

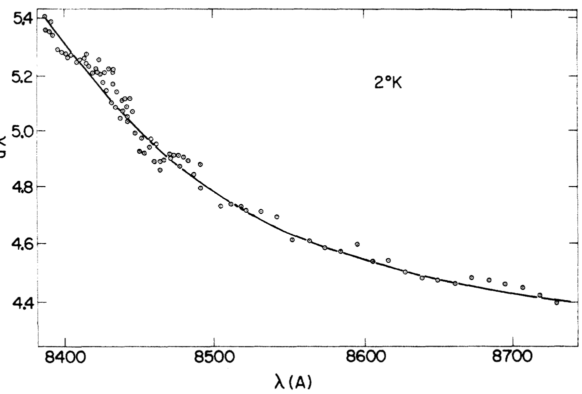

FIG. 3. $(n-\lambda dn/d\lambda)$ vs wavelength. Laser 17-59-1. Substrate doping $=4\times10^{17}$ cm^{-3}.

and stimulated emission becomes important.

From Eq. (1) the separation between successive fringes, $\delta\lambda$, can be found:

$$2l\delta\lambda/\lambda^2=(n-\lambda dn/d\lambda)^{-1}. \qquad (3)$$

Unless the absolute value of n at one wavelength is known, the right-hand side of Eq. (3) is what can be obtained from the data. This is plotted in Fig. 3. It can be seen that $n-\lambda dn/d\lambda$ varies rapidly with λ. This is caused by the fact that the wavelength is very close to the direct absorption edge.[10] The shape of the curve varies with substrate impurity concentration. This effect is being investigated further.

The wavelength of the peak of an oscillation decreases with increasing current as shown in Fig. 2. The decrease is the same at 8390 Å and 8460 Å, but the effect disappears by 8550 Å. This shift corresponds to a decrease of the index of refraction with current. Its wavelength dependence and its magnitude (0.02%) suggest that it is due to a change of absorption associated with the population inversion.

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ANOMALOUS DENSITY OF STATES IN THICK SUPERCONDUCTING LEAD FILMS

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The fine structure in the current vs voltage characteristics of superconductor/barrier/lead tunneling junctions shows a marked dependence on the thickness of the lead film.[1] Here we report a more detailed study using aluminum as the reference superconductor and conclude that this anomalous behavior can best be explained in terms of an effective density of states, $\rho_{\rm eff}(E)$, which differs appreciably from the BCS[2] expression $\rho=E/(E^2-\epsilon^2)^{1/2}$. $\rho_{\rm eff}(E)$ is thought to arise from two parts of the Fermi surface contributing different energy gaps and having different normal densities of states associated with them.

The characteristics were measured as a function of lead film thickness and temperature, and Fig. 1 shows some typical results for three thicknesses at ~1°K. The 0.3-μ film shows no anomaly, but at 0.7 μ a structure becomes apparent which is more pronounced in the 2-μ thick film. Two experiments were performed to ensure that this structure did not arise from (a) nonuniform film thickness caused by migration under the mask, and (b) differential expansion between the glass substrate and the lead film causing lo-