COHERENT LIGHT EMISSION FROM GaAs JUNCTIONS

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Coherent infrared radiation has been observed from forward biased GaAs p-n junctions. Evidence for this behavior is based upon the sharply beamed radiation pattern of the emitted light, upon the observation of a threshold current beyond which the intensity of the beam increases abruptly, and upon the pronounced narrowing of the spectral distribution of this beam beyond threshold. The stimulated emission is believed to occur as the result of transitions between states of equal wave number in the conduction and valence bands.

Several requirements must be fulfilled[1] in order that such stimulated emission can be observed: (a) The electron and hole populations within the active region must be large enough that their quasi-Fermi levels are separated by an energy greater than that of the radiation; (b) losses due to absorption by other processes must be small relative to the gain produced by stimulated emission; and (c) the active region must be contained within a cavity having a resonance which falls in the spectral range within which stimulated emission is possible.

In our structure, the necessary population inversion is produced by injection of carriers from the degenerate n- and p-type end regions of the junction into the transition region. Condition (b) is the most difficult to fulfill, since the stimulated radiation propagates in the plane of the junction where the active region may be only a fraction of a wavelength in thickness and has a wave front which laterally extends many wavelengths into the passive n- and p-type regions bounding the junction plane. Laser action is favored by the large matrix element for band-to-band radiative recombination compared with that for free carrier absorption in GaAs and by the fact that the energy of the emitted radiation is below the absorption threshold of the degenerate material bounding the junction.

The diodes can be described approximately as cubes 0.4 mm on an edge, the junction lying in a horizontal plane through the center. Current is passed through the junction by means of Ohmic contacts attached to the top and bottom faces. The front and back faces are polished parallel to each other and perpendicular to the plane of the junction, in order to satisfy condition (c) above. Current is applied in the form of pulses of 5 to 20 μsec duration with the diode immersed in liquid nitrogen.

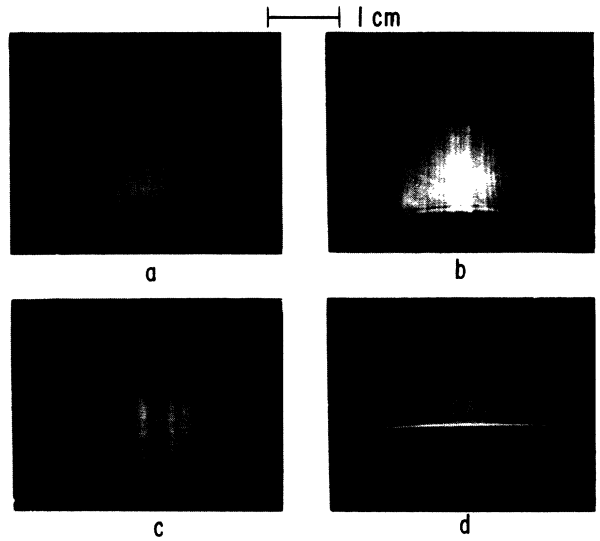

FIG. 1. Radiation patterns observed with image tube a distance d from junction. (a) and (b), diode L-69 below and above threshold, $d = 6$ cm. (c) Diode L-69 above threshold, $d = 15$ cm. (d) Diode L-75, $d = 5$ cm.

We have studied the radiation pattern by means of an infrared converter tube which provides an image that can be examined visually or photographically. Examples of such patterns are given in Fig. 1. The first two photographs show the pattern produced by a diode with the current below and above threshold, with the image converter 6 cm from the diode. Figure 1(c) shows the same diode above threshold with the screen 15 cm away, so that the radiation pattern is correspondingly enlarged. In these photographs the horizontal bands result from interference between the light produced at the junction and its image in the metal disc on which the diode was mounted, and their presence does not imply coherence of the source. On the other hand, the vertical bands which appear only in Figs. 1(b) and 1(c) are due to interference between the waves emitted at various points along the edge of the junction at the front face of the cube, and their appearance is evidence that a definite phase relation exists between the light emitted at various points along the junction, i.e., that the light is coherent. The angular separation between the interference maxima is consistent with the dimensions of the junction and the wavelength of the radiation. However, the relative intensities of the maxima produced by this and other similarly constructed diodes indicate that the radiation is not produced by the most elementary mode of this type of cavity.

Measurements were made of the light intensity from diode L-70 as a function of junction current at 8420 Å on the axis of the beam. Below 5000 A/cm^2 the light intensity varied linearly with current density. Near 8500 A/cm^2 the intensity increased very rapidly with current, reaching a value about ten times the extrapolated low-current intensity at 20 000 A/cm^2. Such a current threshold is characteristic of the onset of stimulated light emission, and it is significant that the azimuthal interference maxima of Fig. 1 make their appearance at this threshold.

Figure 2 shows the spectral distribution measured with the spectrometer located on the beam axis at several values of current density. Below threshold, the spectral width at half maximum is 125 Å, in agreement with the measurements of Keyes and Quist.[2] As the current is increased through threshold, the spectral width decreases suddenly to 15 Å, in a manner which again is characteristic of the onset of stimulated emission. If this 15Å width is due to a single resonant mode so that the emission is homogeneously broadened by the lifetime of this mode, then the oscillations persist only for a period of 1.6×10^{-12} sec or for a time long enough for the radiation to travel 0.1 mm, which is less than the length of the crystal. However, the broadening may instead be due to oscillations occurring at several unresolved modes during the pulse or to a variation in the wavelength of the resonant mode during a pulse. The instrumental resolution was about 3 Å.

Additional modes appear at longer wavelengths when the current is further increased beyond threshold, as illustrated in Fig. 3. The fact that the additional modes appear at lower energy suggests that the principal dissipative process becomes more effective at longer wavelengths, as would be the case for free carrier absorption. The separation of these additional modes is about three times that calculated on the assumption that each corresponds to one additional half wavelength between the plane surfaces, which were 0.32 mm apart in this diode.

Other junctions have been constructed which ex-

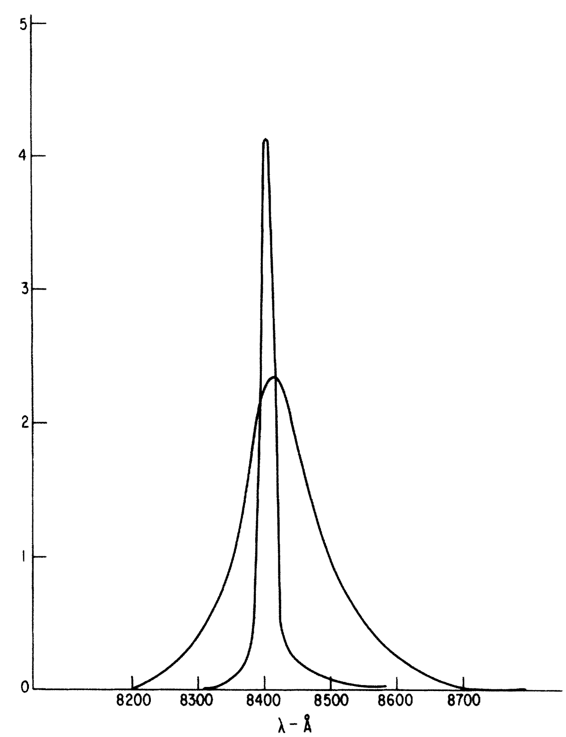

FIG. 2. Spectral distributions from diode L-69 below and above threshold. Different vertical scales.

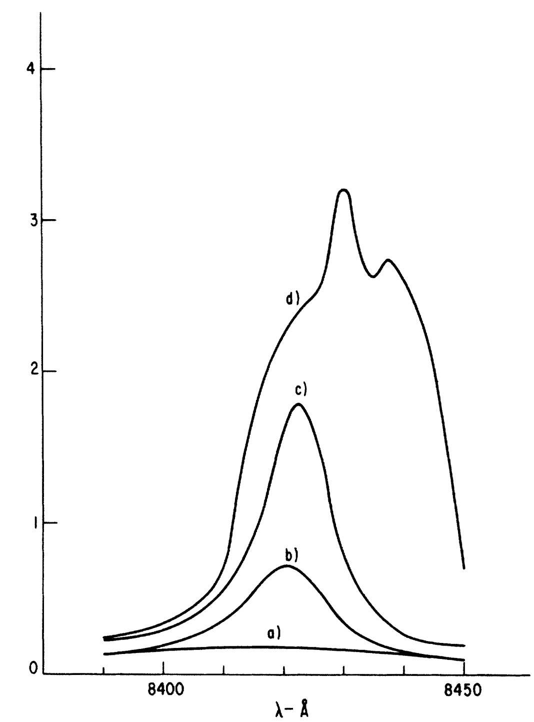

FIG. 3. Spectral distributions of diode L-70 at various currents, same vertical scale for all curves, arbitrary units. (a) 6000 A/cm^2, (b) 8600 A/cm^2, (c) 10 400 A/cm^2, (d) 20 000 A/cm^2.

hibit quite different characteristics. These produce a radiation pattern which is almost uniform in the azimuthal plane, but which is only a few tenths of a degree wide in the vertical plane, as shown in Fig. 1(d). This pattern implies that there is coherence over a distance of the order of 100 μ in the vertical direction but virtually no spatial coherence in the horizontal direction.

While stimulated emission has been observed in many systems, this is the first time that direct conversion of electrical energy to coherent infrared radiation has been achieved in a solid state device. It is also the first example of a laser involving transitions between energy bands rather than localized atomic levels.

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[1]M. G. A. Bernard and G. Duraffourg, Physica Status Solidi 1, 699 (1961).

[2]R. J. Keyes and T. M. Quist, Proc. Inst. Radio Engrs. 50, 1822 (1962).

ELECTRONIC CONDUCTION OF POLYMER SINGLE CRYSTALS

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Electronic conduction at high current densities has been observed in single crystals of linear polyethylene placed between two metal electrodes. The crystals[1] are placed broad side down on a metal substrate which functions as an electrode, while the second electrode consists of a catwhisker. The two electrodes are connected to a zero-impedance power supply[2] with an x-y recorder for plotting the voltage-current graphs. Typical crystals have an area of $10\times20\ \mu^2$ and it is necessary to work under a high-power microscope. Contact pressure and area cannot be kept constant over long periods. Nevertheless, reproducibility of the I-V curves is good for individual crystals on a copper substrate, though fluctuations in thickness and growth of the crystals give rather large variations in the experimental data taken from different crystals. Shorts between catwhisker and substrate show up as straight, nonrectifying I-V curves characteristic of a small residual resistance in the connecting wires and catwhisker.

Figure 1 shows the I-V characteristic of a 100Å polyethylene crystal between Pt catwhisker and Cu substrate (Pt/Cu). At low voltages the curve shows a small rectification ratio with the larger slope in the first quadrant, where a region of negative resistance is found at increased field strength. The same general shape of the I-V curve is observed for Mo or W catwhiskers, but W/Cu has opposite rectification compared to Pt/Cu and Mo/Cu, and current increases with the difference of the metal's contact potential relative to that of copper in air. On most other metal substrates, the visibility of the crystals is not high enough for proper positioning of the catwhisker. However, experiments have been made on the system Au/Au with a 100Å crystal and similarly shaped curves were found with peak voltage and current at lower values (about 60 mV and 10 μA). The gold for substrate and catwhisker may have slightly different contact potential due to differing impurities and to the etching treatment necessary in sharpening the

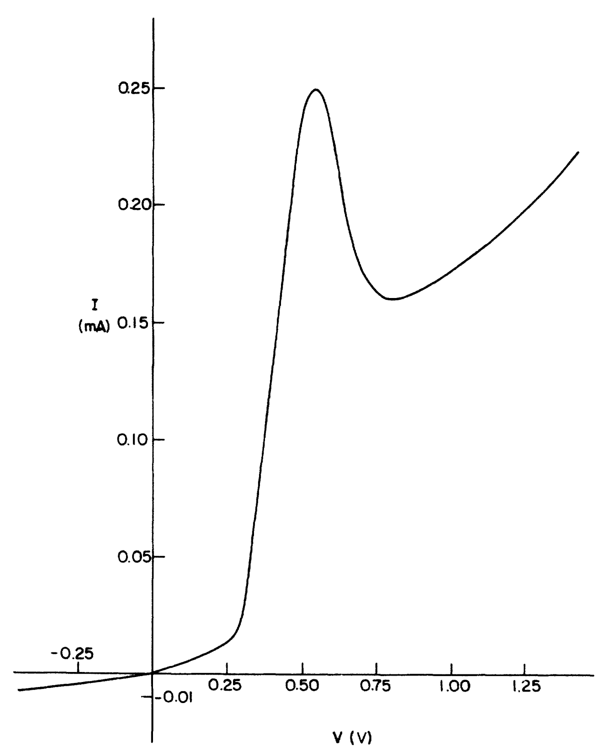
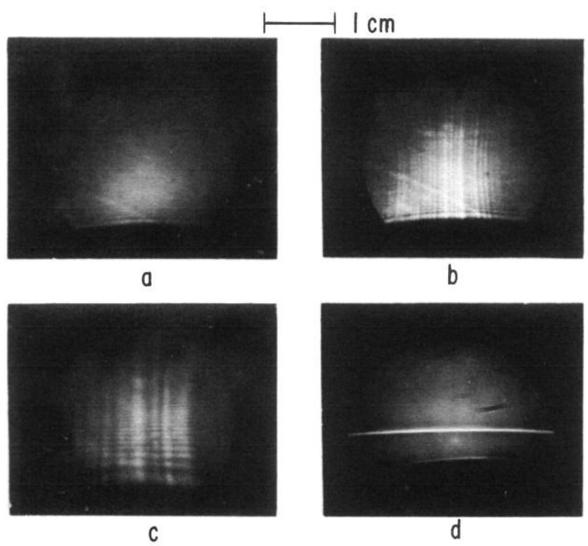


FIG. 1. I-V characteristic of a 100Å polyethylene single crystal between Pt catwhisker and Cu substrate.



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