Since the laser threshold is, by Eq. (1), proportional to d and since $\omega_p^2/\omega^2 \sim 6 \times 10^{-4}$, we would expect essentially equal thresholds for laser oscillations in TE and TM polarizations.

In closing we note that although the dielectric confinement mechanism is, along with the high recombination efficiency, the main reason for the occurrence of laser action in p-n junctions, the mechanism postulated above should be operative in any p-n diode with or without biasing current. As a matter of fact, the experimental verification of the dielectric-waveguide effect in p-n junctions was obtained on nonlasing GaAs diodes.[7]

Useful comments and suggestions by J. K. Galt, R. Kompfner, and J. M. Whelan are gratefully acknowledged.

[1] R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, *Phys. Rev. Letters* 9, 366 (1962).

[2] M. I. Nathan, W. P. Dumke, G. Burns, F. H. Dills, and G. Lasher, *Appl. Phys. Letters* 1, 62 (1962).

[3] T. M. Quist, R. J. Keyes, W. E. Krag, B. Lax, A. L. McWhorter, R. H. Rediker and H. J. Zieger, *Appl. Phys. Letters* 1, 91 (1962).

[4] Amnon Yariv and R. C. C. Leite, Conditions for Spectral Narrowing and Coherent Emission in Recombination Radiation (to be published).

[5] See, for instance, R. E. Collin, *Field Theory of Guided Waves* (McGraw-Hill Company, Inc., New York, 1960).

[6] The term ω_p^2/ω^2 is given, for instance, by N. Marcuvitz in *Electronic Waveguides* (Polytechnic Press, New York, 1958), p 75.

[7] W. L. Bond, B. G. Cohen, R. C. C. Leite, and A. Yariv, Observation of the Dielectric-Waveguide Mode of Light Propagation in p-n Junctions, *Appl. Phys. Letters* 2, 57 (1963).

OBSERVATION OF THE DIELECTRIC-WAVEGUIDE MODE OF LIGHT PROPAGATION IN p-n JUNCTIONS

W. L. Bond, B. G. Cohen, R. C. C. Leite, and A. Yariv
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

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Theoretical considerations of the propagation of electromagnetic energy near a p-n junction[1] show that the "sandwich" formed by having a depletion layer bounded by the p and n regions can act as a dielectric waveguide.[1,2] The confinement of the energy is due to a dielectric discontinuity

$$\delta\epsilon = \epsilon^{(0)}\left(\frac{\omega_p^2}{\omega^2}\right)$$

between the depletion layer and the bounding media. ω_p, the plasma frequency due to free charge carriers, is assumed, for simplicity, to be the same on the p and n sides. This is not far from reality for the GaAs junctions described in this Letter.

The junction waveguide supports both TE and TM propagation. Since the dielectric discontinuity as given by Eq. (1) is very small, $\omega_p^2/\omega^2 \sim 10^{-3}$ is a typical value in degenerate junctions, the lateral dimension (in a direction normal to the junction plane) of these waves is far larger than the thickness of the depletion layer. The decay of the energy density in the normal direction is described by e^{-2px} where p is given by

$$p = \frac{\omega_p^2 t}{c^2}, \tag{1}$$

where $2t$ is the junction thickness and c is the velocity of propagation in the medium.

If we define a penetration depth d as the distance between the two points at which the energy density is down to $1/e$ of its value at the junction we get

$$d = \frac{c^2}{\omega_p^2 t}. \tag{2}$$

INDEXING CATEGORIES

A. lasers	E/T
A. p-n junctions	
A. GaAs(Tl)	
B. dielectric-waveguide effect	

Values of $d \sim 45\ \mu$ have been calculated[1] for GaAs p-n junctions with $2t \sim 0.1\ \mu$ and $N_e \sim 10^{18}/\mathrm{cm}^3$, of the type in injection lasers.[3-5] The threshold current density for coherent laser emission in these lasers is proportional to d and the observed current values are consistent with the above estimate of d.[6]

To demonstrate the existence of the dielectric-waveguide effect we photographed the front surface of a forward-biased GaAs p-n junction at 77°K. The experimental arrangement is shown in Fig. 1. The composite camera includes an image converter to transform the 0.84-μ image of the front surface to a visible one.

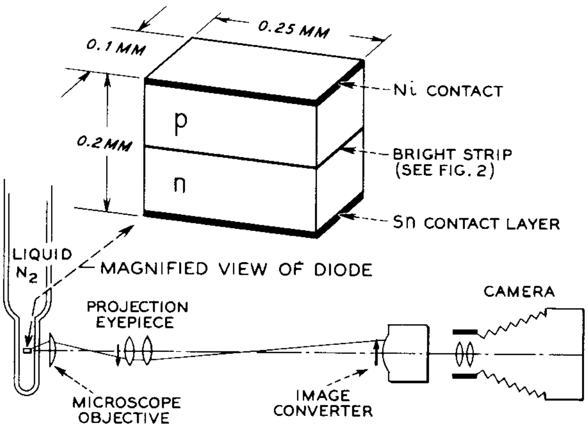

Fig. 1. The experimental setup and an enlarged view of the diode. The pulse biasing equipment is not shown.

In the absence of a dielectric-waveguide effect the recombination radiation will cause a nearly uniform illumination of the diode front surface. When the dielectric confinement described above is present a certain fraction of the energy, ~ 2% in our case,[7] is fed into the waveguide mode. One would expect to see on the junction surface a bright strip of thickness d and a far fainter background due to the isotropic illumination.

In Fig. 2 we show a photograph of a diode biased with 2500 $\mathrm{A/cm}^2$. The presence of the bright region demonstrates the existence of the dielectric-waveguide effect and yields $d \sim 30\ \mu$–$50\ \mu$. The total lack of illumination above the bright region is due to the far greater opacity of the p material, which is above the junction, compared with the n material to radiation at 0.84 μ.

As a further check on the theory we measured the distribution of light intensity in the normal direction

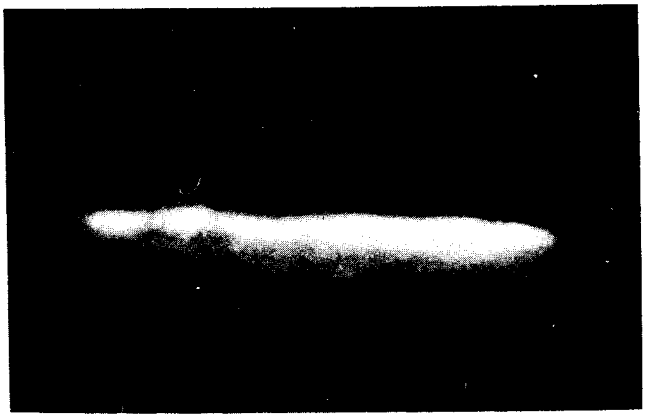

Fig. 2. A photograph of the front surface of the diode in which the bright region corresponds to light confined by the dielectric-waveguide effect.

(away from the junction). This was done by replacing the image converter (see Fig. 1) by a photomultiplier (S-1 response) and scanning the magnified image (×50) of the diode front surface through a 100-μ aperture. The diffuse scattering of the non-polished diode front surface yields an image with a brightness distribution which is proportional to the energy distribution within the waveguide. The results are shown in Fig. 3.

A number of points are noteworthy:

(a) The decay rate is essentially exponential in agreement with the theory.[1]

(b) The deviations from the exponential law in the vicinity of the junction are probably due to gradients in the impurity concentration.

(c) The difference in the exponential factor in the n and p regions is, according to Eq. (2), due to differences in carrier concentration. As a matter of fact, we can deduce from the data and the known ratio of m_e/m_h that $N_h/N_e \sim 20$.

The experiments were performed on two diodes which were produced by diffusing a heavily doped zinc layer into n-type GaAs (doped with tellurium) with $N_e \sim 5 \times 10^{17}\ \mathrm{cm}^{-3}$. The n-type contact was alloyed tin while the p contact was sintered nickel. One of the diodes had cleavage faces with near specular reflection and exhibited laser emission above 8000 $\mathrm{A/cm}^2$. The second diode had scattering (diffusing) surfaces. The same value of d was observed in both diodes over a range of biasing currents between 300 $\mathrm{A/cm}^2$ and 15,000 $\mathrm{A/cm}^2$ so that the observed dielectric-waveguide effect is not due to the presence of stimulated emission. We have

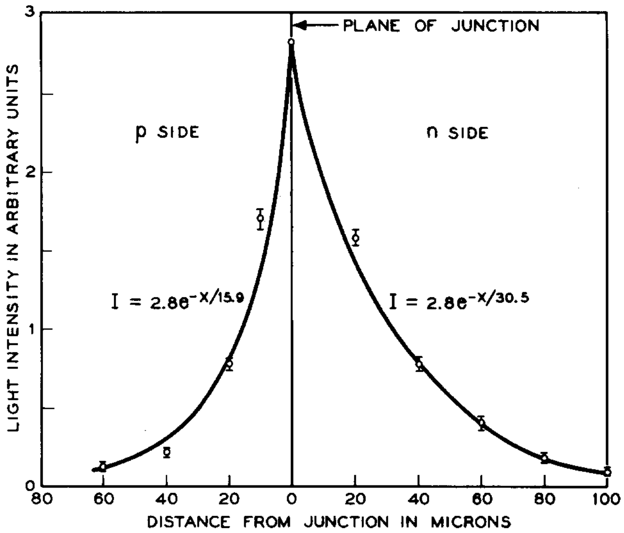

Fig. 3. Distribution of energy across the dielectric waveguide. The solid curves are "best-fit" exponentials. The penetration depth d is $\sim 47\,\mu$.

also ascertained that the measured value of d is independent of the f-value of the optical system.

Reflection of light from the junction boundary in GaP junctions was previously observed and attributed to the dielectric discontinuity by A. Ashkin[8] and M. Gershenzon.

[1]Amnon Yariv and R. C. C. Leite, Dielectric-Waveguide Mode of Light Propagation in *p-n* Junctions, *Appl. Phys. Letters* 2, 55 (1963).

[2]See, for instance, R. E. Collin, *Field Theory of Guided Waves* (McGraw-Hill Company, Inc., New York, 1960).

[3]R. N. Hall, G. E. Fenner, J. D. Kingsley, J. J. Soltys, and R. O. Carlson, *Phys. Rev. Letters* 9, 366 (1962).

[4]M. I. Nathan, W. P. Dumke, G. Burns, F. H. Dills, and G. Lasher, *Appl. Phys. Letters* 1, 62 (1962).

[5]T. M. Quist, R. J. Keyes, W. E. Krag, B. Lax, A. L. McWhorter, R. H. Rediker, and H. J. Zeiger. *Appl. Phys. Letters* 1, 91 (1962).

[6]Amnon Yariv and R. C. C. Leite, Conditions for Spectral Narrowing and Coherent Emission in Recombination Radiation (to be published).

[7]The energy fed into the waveguide mode is, using ray optics, that which undergoes total internal reflection at the junction boundaries. For $\omega_p^2/\omega^2 \sim 10^{-3}$ the critical angle is $\sim 88°$, hence our estimate of $\sim 2\%$.

[8]A. Ashkin, private communication.

PARAMETER CHANGES WITH COLD WORK IN LITHIUM FLUORIDE

D. Lewis and H. Pearson
Crystallography Section, Battersea College of Technology
London, S. W. 11., England

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In a recent letter, Phillips[1] has drawn attention to the effects of heat treatment on the lattice parameter of lithium fluoride. His observations have shown that, after annealing at 500°C, rapid cooling to temperatures below 300°C results in a higher value of lattice parameter than is the case when the specimens are cooled slowly. He ascribes this effect to agglomeration of precipitation of impurities by the slowly cooled specimen in the temperature range 150°-250°C, which permits a faster rate of decrease of yield stress than in the case of the specimen cooled rapidly. In both specimens, however, there is a pronounced discontinuity at 300°C in the temperature vs lattice parameter relationship. During recent studies of line broadening in the alkali halides,[2] a similar discontinuity was noticed, after annealing lithium fluoride at 300°C, in the variation of the lattice parameter and peak breadth with annealing temperature.

INDEXING CATEGORIES

A. alkali halides	**C.** spectroscopy
A. LiF	E
B. peak broadening	
B. lattice parameter	
B. cold-working effects	

It has been observed that lithium fluoride exhibits a greater degree of broadening on cold work than most alkali halides, but the broadening is also associated with a peak shift which is initially towards a lower value of 2 θ for all reflections, indicating a larger parameter value in the worked specimen. After the specimen was worked half an