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Cite as: Appl. Phys. Lett. **1**, 82 (1962); https://doi.org/10.1063/1.1753706
Submitted: 17 October 1962 • Published Online: 23 December 2004

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COHERENT (VISIBLE) LIGHT EMISSION FROM $Ga(As_{1-x}P_x)$ JUNCTIONS*

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(Received October 17, 1962)

Recently Hall, Fenner, Kingsley, Soltys, and Carlson[1] (HFKSC) reported generation of coherent infrared radiation from forward-biased GaAs *p-n* junctions. We wish to report similar generation of shorter wavelength coherent (visible) radiation from forward-biased $Ga(As_{1-x}P_x)$ *p-n* junctions. As in the experiments reported by Hall and others, evidence for coherent light emission in $Ga(As_{1-x}P_x)$ is based upon the observation of a threshold current beyond which the light intensity increases sharply, upon the pronounced narrowing of the spectral distribution of emitted light beyond threshold, and upon the sharply beamed radiation pattern of the emitted light. Again, as in the case described by HFKSC, the stimulated emission is believed to occur as the result of transitions between states of equal wave number in the conduction and valence bands. It is believed this occurs because of the choice of the ratio of P to As in $Ga(As_{1-x}P_x)$ so that the crystal is a "direct" semiconductor.[2]

In the present case the conditions on (1) junction design and doping, (2) degree of inversion (by injection) of carriers in conduction band and valence band states in the junction transition region, and (3) geometrical relationship of the junction plane to the bounding, parallel "cavity" faces for stimulated emission are as described in ref. 1.

Our $Ga(As_{1-x}P_x)$ diodes are rectangular parallelepipeds or cubes with two opposite, parallel sides carefully polished and with an active (junction) area $\sim 10^{-3} cm^2$. In each diode a diffused junction lies 10 μ or deeper from one contact surface into the crystal and is perpendicular to the two polished surfaces. Most of our diodes have been fabricated on *n*-type $Ga(As_{1-x}P_x)$, prepared by the halogen vapor transport and synthesis procedure we have previously described.[3] Donor impurity concentrations greater than $10^{18}/cm^3$ have been employed.

Electrically, the diodes have "clean" V-I characteristics and rise steeply into forward conduction on a scale comparable to that of high quality GaAs *p-n* junctions. As expected, because of the larger (variable) bandgap of $Ga(As_{1-x}P_x)$, the diodes require higher forward voltages than GaAs junctions) [*e.g.*, 1.3 V (diode 28A) as compared to 1.0 V at the "corner" leading to steep current increase]. The overall high quality and efficiency of these junctions is indicated by the fact that in free air (300°K) currents from 20 mA to over 100 mA do not overheat the junctions and are sufficient to produce easily perceptible red light emission.

The evidence for stimulated emission may be conveniently presented by referring to Fig. 1, which represents data taken on diode 28A while it was immersed in liquid nitrogen. Below $\sim$11,000 A/cm^2 the light intensity varied linearly with current (pulsed-current, pulses 1- to 5-μsec long). Above $\sim$11,000 A/cm^2 the light intensity increased sharply with current (super-linear region) and began to assume a narrower pulse width than the somewhat rounded input current pulse. This threshold behavior characterizes the onset of stimulated emission.

As shown by curve (*a*) of Fig. 1 the spectral width below or near threshold (11,000 A/cm^2) was $\sim$125 Å. Although it is not shown on Fig. 1, the spectral width at 16,000 A/cm^2 narrowed to $\sim$20 Å and, as shown by curve (*b*), narrowed to $\sim$12 Å at 19,000 A/cm^2. This, also, is consistent with the onset of stimulated emission. Whereas the GaAs junctions described by Hall and others emitted coherent radiation near 8400 Å, it will be noticed that for diode 28A we have been able to shift the wavelength to a sharply peaked output at 7100 Å.

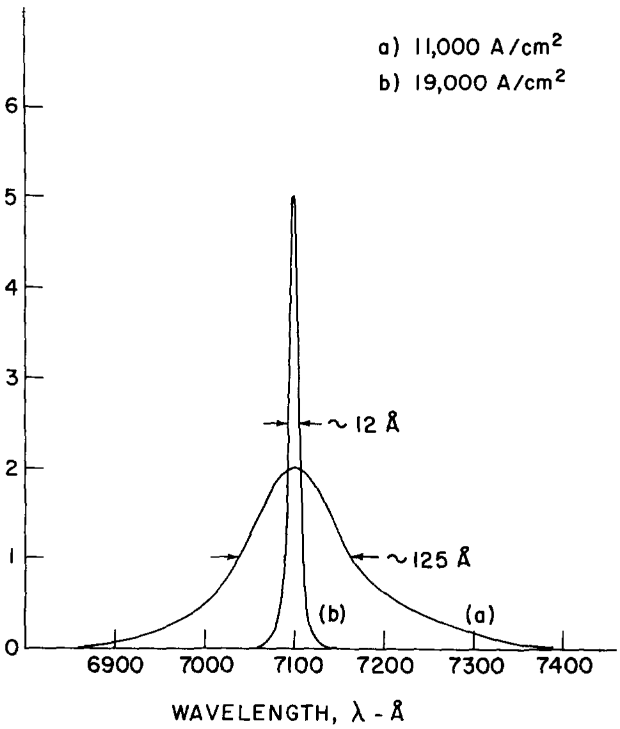

Fig. 1. Spectral distribution of $Ga(As_{1-x}P_x)$ diode 28A at 77°K. (*a*) Below threshold (11,000 A/cm^2) and (*b*) above threshold (19,000 A/cm^2). Different vertical scales.

The radiation pattern from diode 28A was observed in the manner described by Hall and others and exhibited the same general geometrical and diffraction features,[1] thus substantiating the existence of coherent emission.

These and related results on other $Ga(As_{1-x}P_x)$ diodes, and their complete consistency with those of Hall and others, add confirmation and further weight to the generality with which stimulated emission may by produced in various semiconductors.

Specifically, our results in $Ga(As_{1-x}P_x)$ show that a *p-n* junction laser can be built with an output wavelength which can be selected in the range from perhaps below 6200 Å (2.0 eV) to near 8400 Å (1.48 eV). The fact that we observe stimulated emission and a very sharply peaked output from Ga $(As_{1-x}P_x)$ *p-n* junctions implies a well defined band structure, which in turn supports the idea that the random distribution of As and P in $Ga(As_{1-x}P_x)$ has little or no effect in "smearing" band properties.

The authors are indebted to C. V. Bielan, F. A. Carranti, B. G. Hess, and S. J. Lubowski for substantial contributions to the fabrication of $Ga(As_{1-x}P_x)$ junctions, to J. D. Kingsley for spectral measurements, to G. E. Fenner for threshold and radiation pattern measurements, and to J. H. Racette for confirming results from his $Ga(As_{1-x}P_x)$ work.. We are particularly indebted to R. N. Hall for a number of stimulating discussions and helpful contributions to this work.

*This work was partially supported by the Electronics Research Directorate, Air Force Cambridge Research Laboratories, Contract AF 19 (628)–329.

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