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Electromagnetic Mode Population in Light-Emitting Junctions

The original interest in the feasibility of a semiconductor injection laser has been increased by the discovery by S. Mayburg,[1] and R. J. Keyes and T. M. Quist[2] that GaAs junctions have a high quantum efficiency for radiative recombination.

More recently M. I. Nathan[3] has found that an efficient light output approximately linear with injection current density can be obtained with pulsed current densities as high as 10^5 amp/cm^2. At these high current densities and correspondingly high light intensities it is reasonable to inquire into the density of photons within the emitting crystal itself. In this Letter we will present a calculation of the electromagnetic mode population in a light-emitting crystal and show that such modes at high injection currents should be highly excited. A similar calculation of the mode population in GaAs junctions had indicated that, at high current densities, effects due to stimulated emission such as emission line narrowing[4] might be observed. An excited electromagnetic mode population, an electron inversion and also a high radiative transition probability are all necessary conditions for the occurrence of stimulated emission. In direct band gap semiconductors, such as GaAs, it has been shown that for both interband transitions[5] and transition between shallow impurities and energy bands[6] the induced transition probability is sufficient to overcome losses that are due to free carrier absorption.

We shall assume a plane junction of area A and thickness $d << A^{1/2}$. The number of electromagnetic modes η of both polarizations in the crystal containing the junction and also within the emission line of the junction is given by

$$\eta = \frac{2 \cdot 4\pi k^2\, \Delta k}{(2\pi)^3}\, Ad = \frac{n_0{}^3}{\pi^2}\, \frac{E^2\, \Delta E\, Ad}{\hbar^3 c^3},$$

where n_0 is the index of refraction of the crystal, E is the photon energy in the emission line and ΔE the width of this line.

Given the quantum efficiency α of the junction and the injection current $i = jA$, we know the rate with which photons leave the crystal, $dN/dt = \alpha\, i/e$.

The total number of photons N in the crystal can be estimated if in addition we know the average time $\bar{t}$ they spend in the crystal before being externally radiated. In calculating $\bar{t}$ we shall assume that the photons are homogeneously distributed in the crystal and have an isotropic distribution of velocities. The average transit time of photons in the crystal is given approximately by $d\sqrt{3}\, n_0/c$. On each encounter with the surface of the crystal only those photons propagating within a cone of half-angle $\theta = \sin^{-1} 1/n_0$ will not be totally internally reflected. If R is the reflectivity for normal incidence, then the average photon will be reflected approximately $(1-R)^{-1}(1-\cos\theta)^{-1}$ times at the crystal surfaces before leaking out. In actual diodes some photons are lost at absorbing contact materials, etc., but this loss is taken into account in the quantum efficiency α. The total number of photons in the crystal is given then by

$$N = \bar{t}\,\frac{dN}{dt} = \frac{\sqrt{3}\,\alpha n_0 djA}{(1-R)\,(1-\cos\theta)\, ce}.$$

Combining the expressions for N and η we obtain for the average population of an electromagnetic mode

$$\frac{N}{\eta} = \frac{\sqrt{3}\,\pi^2\,\alpha\hbar^3 c^2 j}{n_0{}^2\,(1-R)\,(1-\cos\theta)\, eE^2\,\Delta E}.$$

If we assume $\alpha = 0.5$, $j = 10^5$ amps/cm^2, $n_0{}^2 = 11$, $R = 0.35$, $E = 1.47$ ev and $\Delta E = 0.02$ ev we obtain that $N/\eta = 100$. This indicates that at high currents most of the radiative emission processes are induced rather than spontaneous processes. If there were not an electron population inversion such processes would be absorptive and it would be difficult to see how the light-emitting diodes could be very efficient at such high photon populations or indeed how such high populations could be built up in the first place.

In actual junctions the width and thickness of the crystal volume are comparable, the surfaces may be rough or irregular and the active region of the crystal from which the light originates may be a small fraction of the total volume. All of these conditions serve to decrease the photon population per electromagnetic mode for a given current. However, since in the case of an ideal junction the photon population at 10^5 amps/cm^2 is so high, it is not unreasonable to expect even a rather nonideal structure to exhibit stimulated emission, or conversely to hope that the stimulated emission threshold may be reduced sufficiently such that a cw injection laser may be obtained.

References

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Note added in proof:

Stimulated emission in GaAs diodes has also been observed by R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, *Phys. Rev. Letters* **9**, 366 (1962).

CW operation is reported by W. E. Howard, F. F. Fang, F. H. Dill and M. I. Nathan in the *IBM Journal*, this issue, page 74.

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