ELECTRON-HOLE IMBALANCE IN THE ACTIVE REGION OF QW LASERS, AND ITS EFFECT ON THE THRESHOLD CURRENT.

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Abstract

This study predicts that the electron/hole density ratio in thin quantum wells (QW's) of GaAs/AlGaAs laser diodes with intrinsic QW active regions (QW PIN lasers) can be significantly different from unity and depends on the doping density near the active region. These deviations from local charge neutrality can have significant effects on the laser threshold.

I. INTRODUCTION.

Macroscopic 1-D studies of threshold currents in QW lasers, based on the gain threshold condition and radiative rate equations, have frequently been performed (Ref.[1-4]). Later, efforts have been made to formulate self-consistent 2-D simulators for diode lasers (Ref[5-7]). These simulators are more precise for studying semiconductor lasers and obtaining quantitatively meaningful data on laser performance. Here we describe a particular aspect of the physics of threshold current in ideal lasers.

In macroscopic 1-D investigations of the threshold current dependence on QW width (Ref[2-4]), the balance of mobile charge (n=p), i.e local charge neutrality, has been used as one of the constraints in the quantum well regions of PIN diodes. This is an accurate assumption for any sizable active region, since in normal device operation Poisson's equation does not permit a large build up of net charge. However, for the dimensions of quantum wells this is not strictly valid, since the local charge neutrality is not necessarily preserved. It is difficult to incorporate such charge imbalance into rate equation based simulators without making arbitrary assumptions. We show here that the deviation from charge neutrality follows naturally in the solution of our self-consistent simulator MINILASE (Ref.[6,8]). We also show that this has important consequences for laser threshold currents.

II. INVESTIGATION OF THE EFFECT OF CHARGE IMBALANCE USING A RATE EQUATION MODEL.

We derive the effect on the predicted threshold current that is obtained from a simple rate equation simulator when the n/p ratio is varied, rather than set to 1. We have performed a simulation based on solving the laser gain equation and used the fact that spontaneous emission dominates the diode laser current value at the onset of stimulated emission (Ref[2-4]). We took the quantum well width to be 50 $\mathring{A}$, and the distributed loss factor of 5200m^{-1}, which was taken for consistency with MINILASE simulations, described in more detail later. The relationship between threshold current and the n/p ratio is shown on Fig.1. We see that for this QW structure the nominal threshold current density increases monotonically with the increase in the n/p ratio. The reason for the variation of threshold current with the k=n/p ratio follows logically from the underlying physical model. Consider the following equation for the rate of stimulated emission (r^{st}_{th}) at threshold:

$$r^{st}_{th} = \sum_i B(E_c^{\nu_0,i}, E_v^{\nu_0,i}) \cdot g(E_c^{\nu_0,i} - E_v^{\nu_0,i}) \cdot (f_e(F_c^{th}, E_c^{\nu_0,i}) + f_h(F_v^{th}, E_v^{\nu_0,i}) - 1), \qquad (1)$$

which is used to calculate the quasi-Fermi levels F_c^{th} and F_v^{th} at threshold. Here B is the Einstein coefficient, g is the reduced density of states (assuming no line broadening), f_e, f_h are the Fermi functions for electrons and holes respectively, and $E_c^{\nu_0,i}$, $E_v^{\nu_0,i}$ are the conduction and valence band levels (with respect to minimum of the i-th subband) contributing to lasing mode ν_0. Our calculations for a 50 Å well show that (for the given range of k) ν_0 is always the lowest allowable optical mode. Therefore, g is constant and has non-zero value only for i=1, B is constant, and f_e, f_h are functions of F_c^{th} and F_v^{th} only. Hence equation (1) reduces to

$$r^{st}_{th} = A \cdot (f_e(F_c^{th}) + f_h(F_v^{th}) - 1), \qquad (2)$$

were A is a known factor. Since r^{st}_{th} is fully determined by the gain threshold value $G_{th} = 5200m^{-1}$ (see discussion above), $f_e(F_c^{th})$ and $f_h(F_v^{th})$ must vary by equal and opposite amounts as k varies. Because of the effective mass disparity in GaAs (and most other materials), the slope of $f_e(F_c)$ at F_c^{th} is usually small, while the slope of $f_h(F_v)$ at F_v^{th} is large. For example, $\frac{\partial f_h}{\partial F_v^{th}} \approx 3.7 \cdot \frac{\partial f_e}{\partial F_c^{th}}$ for k=.6, and $\frac{\partial f_h}{\partial F_v^{th}} \approx 44 \cdot \frac{\partial f_e}{\partial F_c^{th}}$ for k=1.5. Therefore, as k=n/p increases, the increase in F_c^{th} is much greater than the decrease in F_v^{th}. Since the calculation of the threshold current involves the summation of terms including $f_e(F_c^{th}, E_c^{\nu,i}) \times f_h(F_v^{th}, E_v^{\nu,i})$ over all optical modes ν and subbands i (see Ref.[1]), it is clear that the large increase in F_c^{th} outweighs the much smaller decrease in F_v^{th}, and the threshold current will increase with k.

III. MINILASE SIMULATIONS.

In order to see whether the n-p imbalance and its effects on threshold current are physically meaningful we turned to the self-consistent 2-D simulator MINILASE, originally described in a previous paper (REF[6]). It consists primarily of the coupled discretized solution of Poisson's equation and the electron and hole current continuity equations, iterated with the photon mode rate equations. The 2-D Helmholtz equation is also solved to determine the transverse intensity profile of the lasing mode(s) (Ref[9]).

The system of the continuity and Poisson's equations is solved by the Newton iteration on its Jacobian. The solution variables of this system are the electrostatic potential and the electron and hole quasi-Fermi levels. In this formalism, there is no rigid local charge neutrality constraint. The physical charge neutrality constraint is globally enforced through Poisson's equation. Since the original publication (Ref[6]), one of the key changes made has been the addition of the Schroedinger Equation for the QW active region, solved iteratively with the continuity-Poisson Newton system. Considering the true quantum nature of the active region, this addition was critical for investigation of any physical effects related to the electronic properties of the active region, notably in our case, the charge distribution and the radiative recombination. For more details see Ref.[8]

The structure considered for our example is the quasi-one dimensional buried Separate Confinement Heterostructure (SCH) laser. This structure has a total width of 3μm and has symmetric material structure. There is a 50Å $GaAs$ QW active region in the middle, then 975Å $Al_{0.4}Ga_{0.6}As$ light guiding regions to each side, followed by 1.4μm $Al_{0.65}Ga_{0.35}As$ regions bounded by electrodes. The doping profiles on this structure were varied in order to achieve the n-p imbalance and investigate the resulting effects. We investigated three different structures. Structure A had the 1.4μm region under the top (bias) electrode p-doped at 5.0×10^{18}cm^{-3} and the 1.4μm region above the bottom (ground) electrode n-doped at 5.0×10^{18}cm^{-3}. The waveguide region was kept intrinsic. Structure B had the top 1.4μm region and the adjacent half of the waveguide region p-doped at 3.0×10^{18}cm^{-3}, while the bottom 1.4μm region was n-doped at 2.0×10^{18}cm^{-3}. The bottom half of the waveguide region and the active region were kept intrinsic. Structure C had the top 1.4μm region p-doped at 3.0×10^{18}cm^{-3}, while the bottom 1.4μm region and the bottom half of the waveguide region was n-doped at 3.0×10^{18}cm^{-3}. The top half of the waveguide region and the active region were kept intrinsic. The doping concentrations were chosen not only to optimize the n-p imbalance in structures B and C, but also to achieve approximate equality of the gain threshold (loss factor) among the three structures. Table I shows the results.

Notice that the threshold current versus k=n/p ratio dependence for these structures follows qualitatively the trend suggested by the simplified calculation that led to Fig.1. Quantitatively, there is about a 25% difference between the threshold current values obtained from MINILASE and listed in Table I and the corresponding points of Fig.1. This difference is acceptable, considering the simplicity of the rate equation model and, in fact, underscores the importance of the self-consistent simulators for accurate quantitative analysis.

Comparing the MINILASE data of Table I for different structures, we note that the lasing threshold current difference between structure B (k=0.66) and structure C (k=1.47) is a very considerable 49.4%. More importantly, we note the difference between structure A, representing a "conventional" PIN laser with n-p neutrality preserved, and structure B, where the heavy p-doping up to the quantum well results in a much higher concentration of holes than electrons in the well. We can see that decreasing the n/p ratio from 1 to 0.66 results in a 15.6% lowering of the threshold current value, which is a significant improvement.

IV. CONCLUSION.

We have shown that, due to a large hole-electron effective mass difference in GaAs, the lowering of the electron concentration in the quantum well relative to that of the holes improves laser threshold performance. This lowering may be achieved by appropriate modulation doping.

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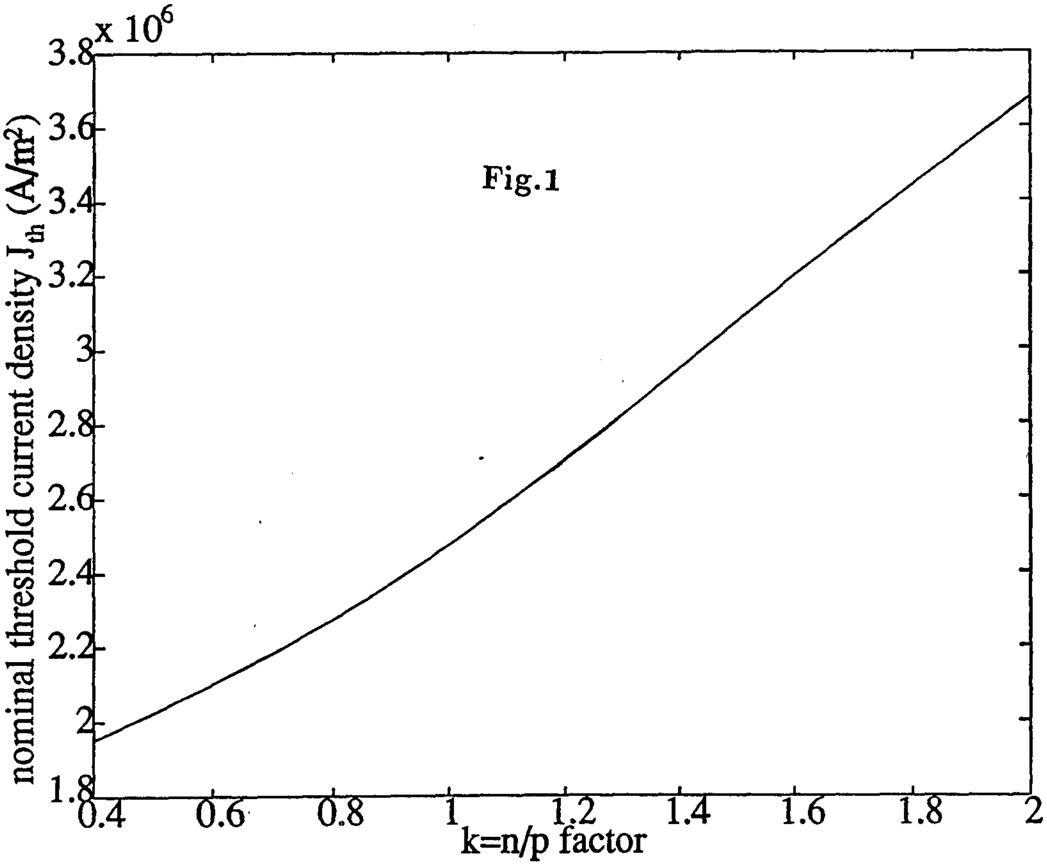

Table I

Structure	k=n/p	$J_{th}(A/m^2)$
A	1.05	$3.38*10^6$
B	0.66	$2.78*10^6$
C	1.47	$4.16*10^6$

Simulation results for structures A, B, and C