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Theoretical Analysis on Nitride-Based Laser Performance

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1. Introduction

Group-III nitride lasers are important because of the many optoelectronic technologies that require coherent emission in the blue-green wavelength region. [1] As these lasers are in an early developmental stage, there is interest in developing an understanding of physical mechanisms, expected device performance, and optimal laser configurations. At present, these issues are difficult to address experimentally because of the difficulty in growing high quality structures of known compositions. This paper approaches the problem from a theoretical aspect, focusing in particular on laser threshold behaviors.

2. Theory

Owing to the strong Coulomb interactions in wide bandgap compounds such as the group-III nitrides, a many-body gain model is required. Our approach involves solving the semiconductor Bloch equations, where collision and screening effects are treated at the level of quantum kinetic equations in the Markovian limit. The details of the calculations are given elsewhere. [2] An advantage of this approach is that it eliminates the dephasing rate as a free parameter. Consequently, the predictions of gain properties are more precise. Equally important, it takes into account physical effects that play important roles in determining experimental shape and carrier density dependence of the semiconductor gain spectra. When applied to the nitrides, our approach provides a consistent treatment of optical behaviors from low electron and hole densities, where excitonic absorption is present, to high carrier densities, where gain is produced by an interacting Coulomb correlated electron-hole plasma.

The input to the gain calculations are the bandstructure properties, specifically the electron and hole energy dispersions, as well as the optical dipole matrix elements. These quantities for a wurzite InGaN/GaN strained quantum well are computed using **k**·**p** theory. The effects of a screened piezoelectric field are taken into account by the iterative solution of the system Hamiltonian and Poisson equation.

3. Results

To obtain the gain vs current density relationship, we begin by calculating the gain spectra for a range of carrier densities. From these spectra, we extract the peak gain as a function of carrier density. The next step involves the calculation of spontaneous emission rates. We performed this calculation using the phenomenological relationship between spontaneous emission and gain spectra. [3] Integrating the spontaneous emission spectrum gives the spontaneous emission rate w_{sp}. The spontaneous emission contribution, or the fundamental limit, to the injection current density is $J_{sp}=ehw_{sp}$, where e is the electron charge, and h is the quantum well width.

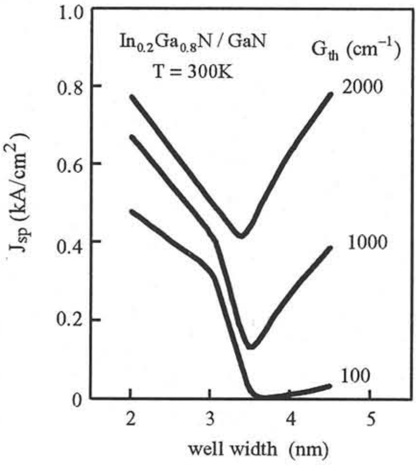

Fig. 1. Spontaneous emission contribution to the threshold current density versus quantum well width for $In_{0.2}Ga_{0.8}N/GaN$, temperature T=300K, and threshold gain G_{pk} = 100, 1000 and 2000cm^{-1}.

Figure 1 shows a result obtained by repeating the above calculations for $In_{0.2}Ga_{0.8}N/GaN$ quantum well structures of different quantum well widths. In the figure, the spontaneous emission contribution to the threshold current density is plotted as a function of quantum well width for three different material threshold gains. We assume operation at gain peak and temperature T=300K. Only the TE (polarization in the plane of the quantum well) polarization is considered because the TM gain is negligible for experimentally realizable carrier densities. The threshold current density is for each quantum well in the active region. For the case of a multiquantum well active region, the total threshold current density is $N_{qw}J_{sp}$,, where N_{qw} is the number of quantum wells. The transparency current is to a good approximation given by the curve for G_{th} = $100cm^{-1}$

An interesting result is the lower threshold current density for the wide (w>3nm) quantum wells. The reason may be understood by noting that for the narrow quantum wells, the relative displacement of the electron and hole eigenfunctions is limited by strong quantum confinement, so that the dipole matrix element is not significantly reduced. As a result, gain for the narrow wells occur at relatively low carrier densities. One the other hand, the weaker quantum confinement makes a wider well more susceptible to piezoelectric field effects. One consequence is appreciable separation between the confined electron and hole eigenfunctions, resulting in significant decrease in the optical dipole matrix element. Only at much higher carrier densities is the piezoelectric field sufficiently screened for gain to be present. However, the reduction in dipole matrix element also results in a lower spontaneous emission rate. According to our calculations, the reduction in spontaneous emission loss in the wide quantum well more than compensates the reduction in gain, so that for the same threshold gain, the wide quantum well device has lower threshold current density.

Our calculations also indicate that gain structures with narrow quantum well widths are sensitive to inhomogeneous broadening, while those with wide quantum well widths are sensitive to nonradiative carrier losses.

4. Conclusions

This paper investigates the theoretical limit to the gain versus threshold current density relation in InGaN quantum well lasers. The analysis is based on a microscopic theory where bandstructure and many-body Coulomb effects, including carrier-carrier collisions are treated consistently. The investigation shows a strong dependence of the threshold current density on the quantum well width, due to the quantum confined Stark effect. We found that the reduced dipole matrix element in the wide quantum well actually benefits laser operation, because the resulting reduction in spontaneous emission loss outweighs the reduction in gain.

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