A TRANSITION MATRIX STUDY OF LASER DYNAMICS

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ABSTRACT

Semiconductor laser dynamics are simulated by a transition matrix approach. We analyze a set of experiments to illustrate the intrinsic gain dynamics of a laser and to clarify the role of various scattering rates in determining carrier relaxation under lasing conditions. We conclude with a study of the effects of photons and hot phonons on gain compression. We find that while hot phonons effects are important, they are not the rate limiting factor of a semiconductor laser.

I. INTRODUCTION:

Recently, there has been considerable interest in the microscopic dynamics of semiconductor quantum well lasers both because of their technological importance and the interesting device physics issues. Although carrier relaxation in quantum wells (QWs) in the presence of carrier-carrier and carrier-phonon interactions has been investigated by a number of experimental and theoretical groups[1], its implication for lasers is less well understood. To understand QW laser carrier dynamics, one must consider ultrafast stimulated emission, carrier thermalization by the large thermal carrier population at threshold, transport in the separate confinement layers, and the capture of carriers from the barrier region to the quantum well itself.

In this paper, we explore the intrinsic response of a quantum well laser systematically using a new transition matrix approach (TMA)[2]. Specifically, we examine the role of electron-electron and electron-nonequilibrium phonon interactions on laser gain and the distribution function. We also study how carrier dynamics are affected by strong electron-photon interactions.

II. TRANSITION MATRIX APPROACH:

Briefly, the TMA is a Monte Carlo technique to directly solve the time dependent but space-independent Boltzmann equation. A transition matrix relates the distribution of particles (electrons, phonons, or photons) at a given time t to the particle distribution at time $t + \delta t$. For density independent scattering events, such as carrier relaxation in absence of light or Coulomb interaction, this matrix is time invariant, however, when the scattering processes depend on the density, then this matrix will evolve in time. To compute the transition matrix, the input momentum space is first divided into a large number of bins, a large number of particles is injected in each of these bins, and these particles are tracked for a time δt by a 2-D Monte Carlo simulation [2,3]. At this point, positions of the particles in momentum space are noted, and the ratio of the particles for a pair of initial and final bins gives the transition matrix element. If one has a initial distribution of particles in momentum space, by repeatedly multiplying the evolving distribution by the transition matrix, one can track particle evolution as a function of time.

Our model includes electron, phonon, and photon dynamics. Electron transport has been treated semiclassically. The scattering mechanisms included are polar optical phonons, acoustic phonons, and electron-electron scattering [3]. Static screening was assumed for e-e scattering, but dynamic screening can be readily treated by the TMA. Transition matrix elements were first computed assuming that the destination states were always empty and the partner state (for electron-electron scattering) was always full. During simulation, one obtains dynamic estimate of the distribution function, f, and the matrix elements are modified accordingly. For example, ee scattering matrix element at the n-th time step is given by

$$t_{ij,mn}^{(n)} = t_{ij,mn}^{(0)} f_j^{(n)} (1 - f_m^{(n)})(1 - f_n^{(n)}), \tag{1}$$

where $t_{ijmn}^{(0)}$ is the scattering rate of an electron at state i colliding with a particle at state j, with final destination to states m and n. This rate was computed by assuming that $f_j^{(0)}$ equals unity and $f_m^{(0)}$ and $f_n^{(0)}$ equal zero. At each time step, this rate is then modified by the Fermi factors as shown above to account for the band filling effects.

We considered hot phonon effects by solving a Boltzmann equation for phonons in the relaxation time approximation [4]. The phonons emitted during a time step are sorted according to their wave-vectors, q. In the next time step, a fraction of these phonons will be reabsorbed, and some of the phonons will decay by nonelectronic means with a finite lifetime. The excess phonons affect the POP scattering rates in the following way,

$$t_{ij}^{(n)} = t_{ij}^{0} \frac{N_q^{(n)} + \frac{1}{2} \pm \frac{1}{2}}{N_q^{(0)} + \frac{1}{2} \pm \frac{1}{2}}, \tag{2}$$

where t_{ij} is the POP scattering rate from state j to state i, $N_q^{(0)}$ is the equilibrium phonon population and $N_q^{(n)}$ is the phonon population at n-th time step.

Finally, the electron-photon interaction is described through standard multiband effective mass formalism. The hole bandstructure was computed by using a 4x4 k.p Hamiltonian for the quantum well. The optical transition matrix elements were computed using polarization and wave-vector dependent band to band scattering rates assuming strict wavevector and energy conservation. The dynamic, energy dependent broadening of the joint density of states were subsequently accounted for by a energy dependent Lorenzian broadening factor [5].

III. RESULTS:

Using the model described above, we discuss three sets of experiments to clarify gain dynamics issues. First, we analyze a pump-probe experiment in which the quantum well is initially empty, next we discuss pump-probe experiments for a gain-inverted laser diodes operated in the amplifier mode, and finally, we examine the effects of gain compression and hot phonons on laser performance.

In the first type of experiments, the quantum well may either be empty or modulation doped. A light pulse excites carriers from the valence band to the conduction band, and a delayed laser beam then probes the carrier distribution as it relaxes. These experiments study carrier relaxation in quantum well via POP and electron-electron scattering. Since they have been simulated in detail by Goodnick and Lugli [3], they provide a good test for our approach.

In this simulation, we use a rectangular laser pulse to excite carriers at 0.23 eV above the conduction band. Figure 1 shows the relaxation dynamics as a function of time. Initially, carriers relax by emitting polar optical phonons. Therefore, the distribution function develops a set of well defined peaks separated by the phonon energy (35 meV). At higher densities, these peaks are washed away be electron-electron scattering within 800 fs; at lower densities, the peaks persist for a longer time. These conclusions are in reasonable agreement with Goodnick's results, which were obtained by direct Monte Carlo simulation.

The second set of experiments, also a pump-probe variety, are more relevant to laser gain dynamics. In these experiments, facets of a laser diode are coated with an antireflection coating, so that it operates in the amplifier mode. Various bias currents put this diode in various levels of

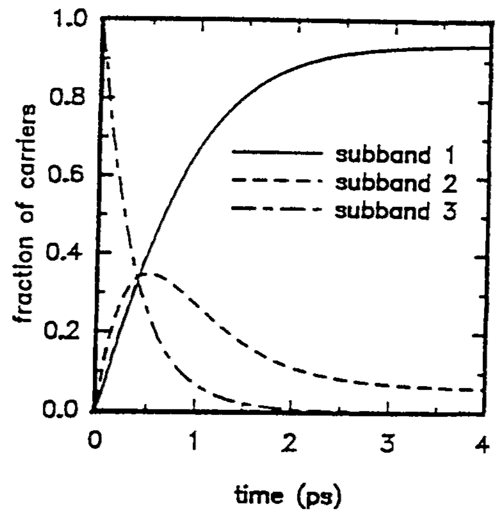

Fig. 1 Relaxation of carriers in an AlGaAs/GaAs/AlGaAs QW. Carriers are injected at t=0 into the third subband and they subsequently relax too subband 1.

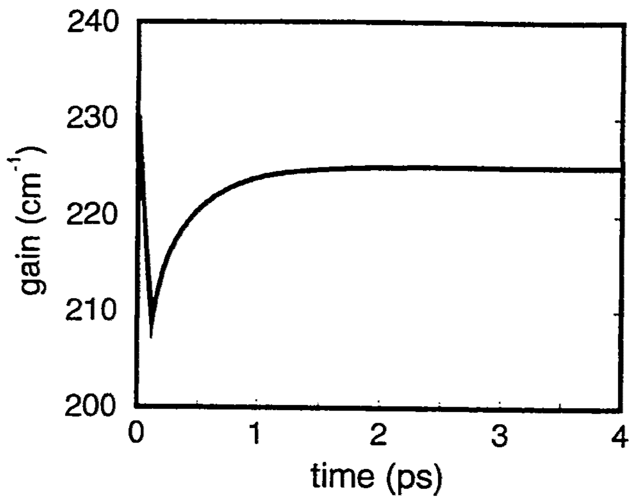

Fig. 2 The gain dynamics of a 150 A QW after a 100 fs of TE laser pulse.

inversion. A pump beam is then launched in the cavity. Depending on the bias level, the pump beam will either stimulate emission (in gain region) or stimulate absorption (in the loss region). A delayed probe beam, as before, monitors the distribution function as the spectral hole is filled in or as the spectral 'heap' diffuses away (in energy). This experiment is relevant to lasers, because lasers are generally biased near threshold, so the nature of screening and the relative importance of various scattering events is expected to be very similar. This is also a significantly more difficult system to describe by simulation, because the change in probe gain may be only a few percent, therefore, noise in the simulation is unacceptable.

Figure 2 shows the dynamics in the gain region. The pump beam is a rectangular pulse of 100 fs duration. The lowest subband population goes down immediately due to stimulated emission, so does the probe gain. Within a few ps, the subband population relaxes by redistributing the carrier population and the relaxation time of $\approx$ 0.72 ps is well within experimental range. As the spectral hole fills up, so does the gain. The gain finally saturates at a lower value, however, because of net decrease of carrier concentration in the quantum well. In the absorption region, on the other hand, electrons are pumped into the conduction band. The increase in number of carriers is reflected in both gain spectrum and subband population. Also, the net increase of carriers is reflected in higher saturated values for gain. In both the gain and absorption region, the average energy goes up - cold carriers are removed in the gain region from the conduction band, hot carriers are added in the loss region.

The role of electron-electron scattering is significant in these experiments and needs some discussion. When a spectral hole is burned in the distribution function by a pump beam, e-e scattering is not very effective in filling up the hole, because electron-electron scattering requires two empty final levels, and the spectral hole provides only one. This explains why it takes picoseconds to fill up a spectral hole, as opposed to femtoseconds as one would expect for a system dominated by electron-electron scattering. Therefore, the time requirement is more consistent with phonon scattering requirements.

Finally, we discuss gain compression and hot phonon issues. Gain compression is a important figure of merit, and it affects the maximum frequency of oscillation and maximum gain in a very significant way. Recently, there has been a lot of discussion on the factors determining gain including band filling effects, spectral hole burning, hot phonon effects. We can now address these issues from

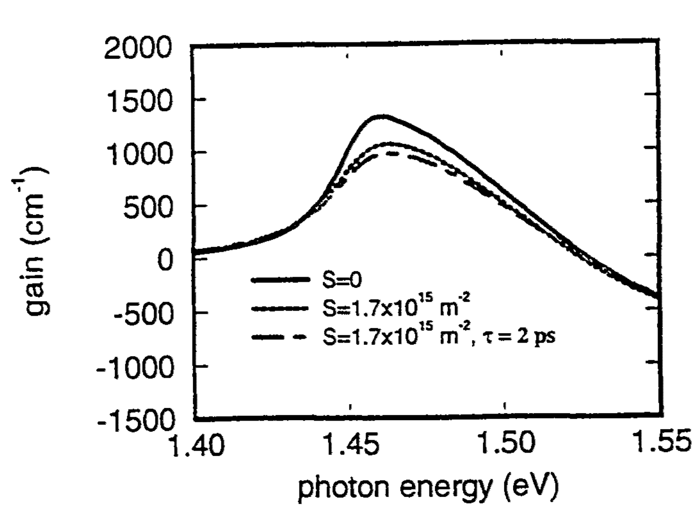

Fig. 3 Gain compression due to stimulated emission and hot phonon effects.

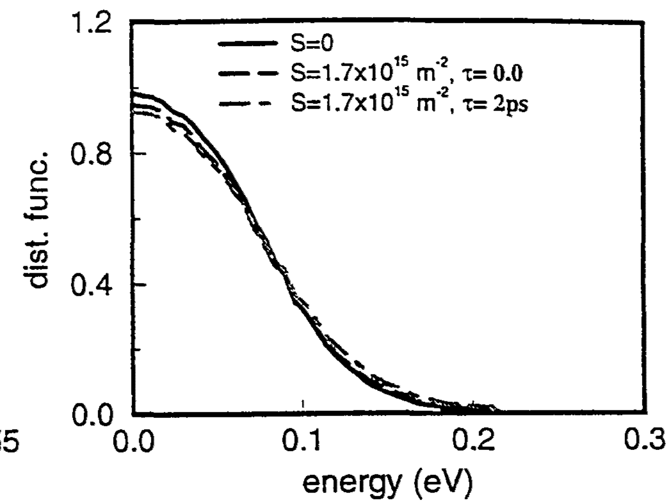

Fig. 4 Electron distribution function at subband 1 in the presence of stimulated emission and hot phonons.

a semiclassical point of view.

Figure 3 shows three gain curves, and Fig. 4 shows the corresponding distribution functions. The first one is the gain curve for a laser biased to $3.0\text{x}10^{16}$ per m^{-2} without any light or hot phonon effects. Broadening due to polarization dephasing has been accounted for by including both the inscattering and outscattering rates of POP and e-e scattering. The second curve is the gain curve in presence of photons ($1.7\text{x}10^{15}$ m^{-2}) at 1.46 eV. If we increase phonon lifetime, there is even larger heating and gain compression. In the first case, the gain compression factor is $1.2\text{x}10^{-16}$ m^{-2}, in the second case this factor increases to $1.6\text{x}10^{-16}$ m^{-2}. If a photon lifetime of 2 ps is assumed, then the maximum frequency of oscillation is 195 GHz without hot phonons and 187 GHz with hot phonons. In contrast to recent phenomenological treatments, we conclude that the net effect of hot phonons is not very significant, and intrinsic dynamics is not the rate limiting factor of diodes now in fabrication.

IV. SUMMARY:

Using a new transition matrix approach, we have analyzed a set of experiments to clarify the gain dynamics of quantum well lasers. Our investigation sheds light on gain dynamics explored by recent pump-probe experiments. Also, we find that gain compression due to hot phonons is not as significant as it was previously thought. We ascribe this to the q dependence of hot phonon effects. To understand the gain dynamics of issues one should also include transport, this is a research issue we shall investigate in the future.

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