Emission dynamics of a magnetoexciton quantum-dot microcavity laser

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We investigate the stimulated emission properties of an $In_{0.18}Ga_{0.82}As/GaAs$ quantum-well microcavity laser under strong magnetic confinement. The dynamics depend sensitively on excitation intensity and cavity mode energy, but show no magnetic-field dependence over a wide range of excitation conditions. The results evidence a fast relaxation which is uninhibited by the quasi-three-dimensional quantum confinement, and may indicate an advantage in designing quantum dots with equidistant energy levels, where Coulomb scattering via an Auger process is expected to be highly efficient. [S0163-1829(97)51008-3]

Great advances have been made in semiconductor lasers over the past decade by the introduction of quantum wells (QWs) as gain media, resulting in lasers with higher inversion, lower lasing threshold, and higher quantum efficiency. The ultimate goal in quantum confined systems is the quasi-zero-dimensional quantum dot (QD), whose δ-function-like density of states could make great inroads towards the improvement of semiconductor lasers.[1] Lasing has recently been demonstrated from self-formed $In_xGa_{1-x}As$ (Ref. 2) and InP (Ref. 3) QDs.

In order to realize the full potential of QDs as gain media, it is essential to understand their relaxation dynamics. Carrier relaxation in bulk semiconductors occurs primarily through longitudinal optical (LO) phonon emission. In QDs, strong three-dimensional quantum confinement creates a large separation between the quantum confined energy levels. When the level separation is larger or smaller than one LO phonon energy ($\hbar\omega_{LO}$), carriers relax via multiple LO and/or acoustic phonon emission, which could possibly result in relaxation times as long as nanoseconds.[4,5] In a semiconductor laser, a fast relaxation process is crucial in order to populate the upper lasing level and sustain a population inversion. Hence a phonon bottleneck could pose a severe limitation to the success of the QD laser.

Recent measurements on GaAs (Ref. 6) and $In_xGa_{1-x}As$ (Refs. 7 and 8) QDs have supported the proposed phonon bottleneck. Other experiments on $In_xGa_{1-x}As$,[9,10] InAs,[11] InP,[12] CdSe,[13,14] and GaAs (Ref. 15) QDs evidence fast relaxation. A recent study of InP QDs demonstrates a slower relaxation if only acoustical phonon emission is possible, but still exhibits relaxation rates which are much faster than theoretically predicted.[16] Some suggested explanations for fast relaxation in these systems include coupling to deep-level traps or interface states.[17,18] Other explanations rely on intrinsic mechanisms in ideal QDs such as rapid relaxation via multiphonon processes,[19] Auger recombination,[20,21] and electron-hole interactions.[22] Bockelmann *et al.* have shown that Coulomb scattering is an important relaxation mechanism in QDs with closely spaced energy levels.[15]

A QW in a strong perpendicular magnetic field provides an ideal, quasi-zero-dimensional system with few surface defects. The magnetic field quantizes the continuum into discrete Landau levels whose spacings are nearly equidistant and governed by the magnetic-field strength.[23] When a QW microcavity laser is subjected to a strong magnetic field, the rate at which the upper lasing level is populated will be governed by relaxation rates between Landau levels. If a phonon bottleneck were to exist in this system, we would expect to see a significant increase in the rise time required to reach maximum laser emission at high magnetic fields, following femtosecond excitation to a high energy level. Previous studies of QW lasers in high magnetic fields have shown reduced spectral linewidth,[24] reduced temperature sensitivity,[1,25] and increased threshold current.[25]

In this paper, we investigate whether the proposed phonon bottleneck will inhibit relaxation in a magnetoexciton QD microcavity laser. We measure the time-resolved stimulated emission from a QW microcavity in magnetic fields up to 12 T. We find that the rise time required to reach maximum emission depends strongly on excitation conditions, but is not influenced by magnetic field. This is direct evidence that the quasi-three-dimensional quantum confinement does not inhibit a fast relaxation. Since the magnetoexciton QD is an ideal system with few surface defects, the absence of a phonon bottleneck must arise from intrinsic effects.

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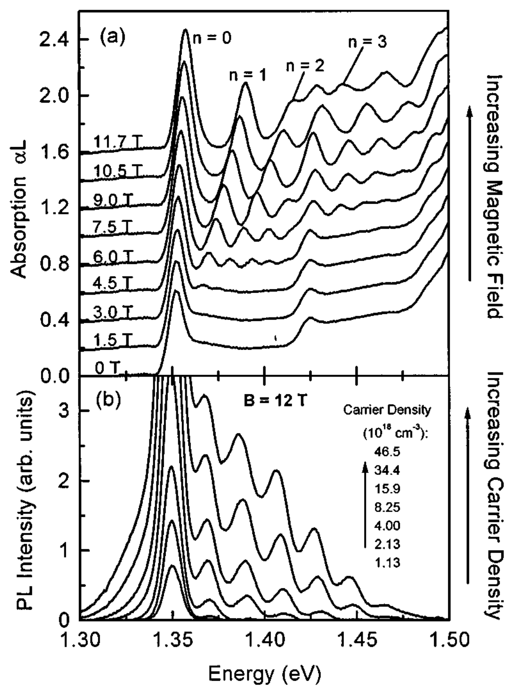

FIG. 1. (a) Absorption spectra of 5.5 nm $In_{0.18}Ga_{0.82}As/GaAs$ multiple quantum wells for increasing magnetic fields. The curves are vertically offset by 0.2. (b) Photoluminescence spectra at 12 T magnetic field for increasing carrier densities, showing pronounced Landau levels even at high densities. The sample was excited at 514 nm.

The magnetoabsorption spectra of Fig. 1(a) were measured on a multiple QW reference sample containing ten clusters of three 5.5 nm $In_{0.18}Ga_{0.82}As$ QWs with 15.5 nm GaAs barriers, and separated by 37.2 nm GaAs layers. The $In_{0.18}Ga_{0.82}As$ QWs have the advantage that the strain pushes the light-hole transition to higher energy, 73 meV above the heavy-hole transition. When a large magnetic field is applied in Faraday geometry, we observe pronounced Landau levels and a region of very low absorption between the lowest magnetoexciton transition and the first Landau transition. Furthermore, the photoluminesence spectra of Fig. 1(b) show well-separated Landau levels at 12 T, even at extremely high carrier densities. The lasing threshold occurs near 2×10^{18} cm^{-3}, corresponding to the lowest carrier densities in the data of Fig. 1(b). Also note that there is no energy shift of the Landau level peaks with increasing excitation. The continuum luminescence does not drop completely to zero between Landau levels, which could be attributed either to overlap between different hole Landau levels or to electron level broadening. (Note that the Landau level spacing in photoluminescence is considerably smaller than in absorption, which we attribute to a change in the reduced mass caused by hole localization at islands formed on the QW interface.[26]) There is, however, significant quantization at these high densities. This situation should be near-ideal for seeing a slower relaxation due to quantization-induced inhibition of phonon emission.

The Landau level spacing is given by the cyclotron energy $\hbar\omega_c=\hbar eB/\mu c$, where B is the magnetic field and μ is the reduced mass. From plotting the fan diagram of absorption peak energies versus magnetic field, we have found the cyclotron energy to be $\hbar\omega_c$ [meV]$\approx$2.25B [T]. Hence the Landau level splittings at 4, 8, and 12 T magnetic fields are 9, 18, and 27 meV, respectively. These splittings are smaller than $\hbar\omega_{LO}$ (36 meV in GaAs), and so we would expect any phonon relaxation between Landau levels to occur via acoustic phonon emission.

The microcavity laser was grown by MBE on a GaAs substrate and consists of a 1λ GaAs spacer at 920 nm sandwiched between 14 and 22.5 period GaAs/AlAs Bragg mirrors, with mirror reflectivities of 99.45% and 99.94%, respectively. Three QWs identical to those in the reference sample were placed at the cavity center. The cavity spacer thickness decreases with radial distance, allowing the cavity mode to be tuned to the minimum threshold energy by moving the pump beam across the sample.

The sample was held at 15 K and excited in a reflectivity minimum 150 meV above the exciton resonance (approximately four times $\hbar\omega_{LO}$) by 2 ps pulses from a mode-locked Ti:sapphire laser with 80 MHz repetition rate. The microcavity emission was dispersed in a 0.32 m spectrometer and then detected by a synchroscan streak camera. The spectral and temporal resolution are 1 meV and 7 ps, respectively.

Since the emission dynamics depend strongly on the cavity mode energy,[27,28] the cavity mode was always tuned to the minimum threshold position, which corresponds to the peak of the gain spectrum. This position varies with magnetic field due to the diamagnetic shift of the exciton. The lasing dynamics depend even more strongly on carrier density, which also changes with magnetic field due to the change in absorption at the excitation energy. This absorption change causes the minimum threshold excitation power to increase with increasing magnetic field. In order to achieve a constant carrier density, we adjusted the excitation power at each magnetic field to maintain a constant total integrated emission.

Figure 2 shows the 920 nm laser emission following 2 ps excitation at zero magnetic field and for increasing pump intensities, from just above threshold at 1.2kW/cm^2, to well above threshold at 1.9kW/cm^2. After the initial excitation, there is a rise time to maximum emission on the order of 40–70 ps due to carrier relaxation and the subsequent build-up of the upper lasing level population. This build-up is followed by fast stimulated emission, and the eventual transition into spontaneous emission. The inset shows a sharp decrease in rise time with increasing excitation, which can be attributed to increased carrier-carrier scattering. The emission decay time also decreases with increasing excitation due to a faster stimulated emission rate.

Figure 3 demonstrates identical emission dynamics at magnetic fields of 0 T and 4 T for a constant carrier density, and with the cavity mode tuned at each magnetic field to the minimum threshold position. The change in the rise time to maximum emission versus magnetic field is plotted in the inset. Even at magnetic fields as high as 12 T, where the magnetoabsorption spectra exhibit deep and well-separated Landau levels with a splitting of 27 meV, there is no increase in the rise time. These results were consistent over a wide range of excitation intensities, from just at threshold to several orders of magnitude above threshold. They indicate that, within our 7 ps time resolution, there is no slowing down of the carrier relaxation due to the quasi-three-dimensional quantum confinement.

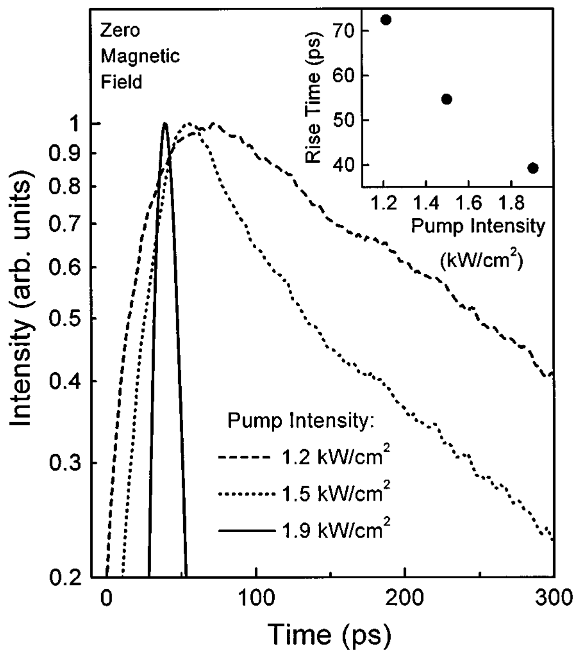

FIG. 2. Time evolution of 920 nm emission from an $In_{0.18}Ga_{0.82}As$ microcavity laser in zero magnetic field, after 2 ps pulsed excitation and for increasing pump intensities. The inset shows the rise time to maximum emission versus pump intensity.

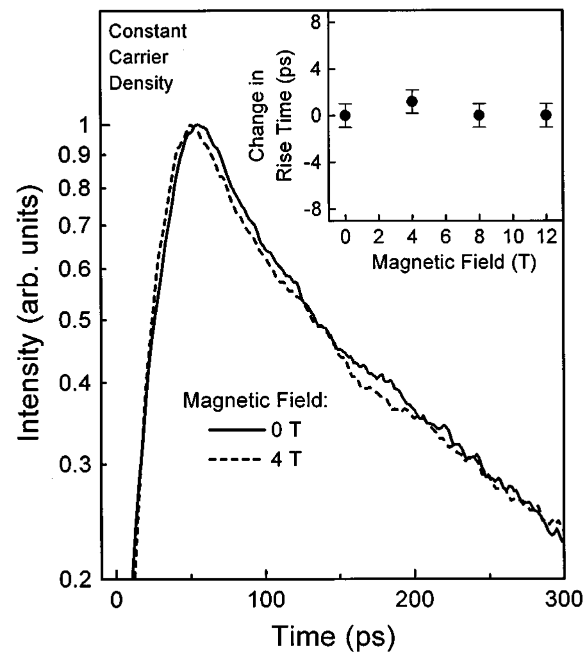

FIG. 3. Time evolution of laser emission at 0 T (solid line) and 4 T (dashed line), for a constant carrier density, showing identical emission dynamics. The inset shows the change in the rise time to maximum emission (with respect to 0 T) versus magnetic field.

One special property of Landau quantization is the approximately equal distance between Landau levels (neglecting nonparabolicity of the electron effective mass). Time-resolved measurements of electron relaxation between Landau levels in bulk GaAs have shown that the equal spacing leads to a very efficient Auger relaxation.[29] Coulomb scattering via an Auger mechanism should also lead to rapid relaxation in QDs, particularly at high carrier densities.[15] The fast rise times presented here therefore indicate a possible advantage in designing QDs with equidistant energy levels by using a parabolic confinement potential. Relaxation via scattering with holes, which have closely spaced energy levels, might be another important contribution to the fast relaxation. The combined relaxation of electrons, holes, and LO phonons could all lead to the fast rise of stimulated emission in these experiments.

In summary, we have measured the time-resolved stimulated emission properties of an $In_{0.18}Ga_{0.82}As$ QW microcavity which has been transformed to a QD laser by a large magnetic field. We observe a strong dependence of the emission dynamics on excitation intensity and cavity resonance energy, but no dependence on magnetic field. Since the rise time to maximum emission is determined by the carrier relaxation rate, the results show that the carrier relaxation is uninhibited by the strong magnetic confinement. The magnetoexciton QD is an ideal system with few surface defects. Hence the absence of a phonon bottleneck must arise from intrinsic relaxation mechanisms, such as Auger recombination or other Coulomb scattering. These findings may also indicate a particular advantage in designing quantum dots with equidistant energy levels, where Auger relaxation is expected to be highly efficient. Finally, the results offer continued hope towards the success of the QD laser.

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