Ultrafast dynamics of InAs/GaAs quantum-dot microdisk lasers

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The dynamical response of InAs/GaAs quantum-dot microdisk lasers has been experimentally investigated using femtosecond optical pumping. Because surface recombination and carrier diffusion are suppressed in the quantum dots, the response speed of a quantum-dot microdisk laser is much faster than that of a quantum-well microdisk laser. A turn-on time as short as 7.8 ps has been achieved in a quantum-dot microdisk laser at 5 K. The temperature dependence of the dynamical response of the quantum-dot microdisk lasers has also been studied over a wide temperature range. At the same pumping level, the turn-on time of the laser decreases as the temperature increases from 5 to 120 K. Such behavior may be due to a faster carrier relaxation process at higher temperature. © 2001 American Institute of Physics. [DOI: 10.1063/1.1376437]

Semiconductor microdisk lasers are of great interest for future low power applications due to their small cavity volume and high quality Q factor for whispering gallery (WG) modes.1–3 Besides the low power consumption, a fast response to external pumping is important for many laser applications, especially in high-speed optical communications. Previously, we have investigated the dynamical response of a GaAs/AlGaAs quantum-well (QW) microdisk laser. It is found that the speed of a QW microdisk laser is limited mainly by the carrier diffusion in the disk plane. The shortest turn-on time of a GaAs/AlAs QW microdisk laser under femtosecond optical pumping is around 100 ps.4 In order to improve the speed of the microdisk lasers, the carrier diffusion process must be eliminated. Very recently, lasing has been achieved in InAs quantum dot (QD) embedded microdisk cavities.5,6 In this letter, we will report our experimental study of the dynamical response of microdisk lasers with QDs as the active media.

The sample investigated in our experiments consists of a 300 nm GaAs buffer layer, 500 nm Al0.7Ga0.3As, 45 nm GaAs, 2 monolayer InAs QDs, and 45 nm GaAs. The sample is grown by molecular-beam epitaxy on a (100) semi-insulating GaAs substrate. The photoluminescence spectrum of the unprocessed wafer is centered around 970 nm with a full width at half maximum (FWHM) of 20 nm at 77 K.

The microdisks are fabricated by electron beam lithography and two-steps of a wet etching process.5,7 The diameter of the disks is 3 μm. Each disk is supported by a 500 nm long Al0.7Ga0.3As pedestal. The thickness of the disk is designed to be 90 nm so that it only supports the lowest order transverse electric (TE) mode in the direction perpendicular to the disk plane. The microdisk is optically excited by 200 fs pulses from a mode-locked Ti:Sapphire laser with the repetition rate of 76 MHz. The excitation wavelength is fixed at 780 nm (1.59 eV). The emission from the side of a microdisk is measured simultaneously by a synchroscan streak camera and a 0.5 m spectrometer with a cooled charge coupled device array detector. The temporal resolution of the streak camera is 2 ps. The spectral resolution of the spectrometer is about 0.15 nm.

Figures 1(a) and 1(b) show, respectively, the time-integrated spectra and time-resolved traces of microdisk emission for several pump powers at a temperature of 5 K. In Fig. 1 (a), several lasing modes have been found at 912.5, 916.2, and 936.9 nm, which correspond to the WG modes of TE22,1, TE17,2, and TE21,1, respectively. Lasing threshold is about 20 μW. In the time-resolved traces shown in Fig. 1 (b), the first peak corresponds to the scattered pump pulse, acting as the zero of the time marker. After a certain delay, the emission from the microdisk reaches its maximum and then decays. In this letter, we define the emission turn-on time as the time difference between the pump pulse and the maximum of the emission pulse. When the incident pump power is less than 20 μW, the emission signal is quite weak, and the time it takes to reach the maximum gradually increases as the pump power increases. However, when the pump power exceeds 20 μW, the emission signal becomes much stronger and the emission turn-on time begins to decrease with increasing pump power. Figure 2 plots the corresponding turn-on time as well as the spectrally integrated emission intensity as a function of the pump power. When the pump power exceeds 20 μW, the emission intensity increases abruptly. At the same time, the spectral linewidth of the emission peaks shown in Fig. 1(a) is reduced, e.g., the FWHM of the peak at 916.2 nm narrows to 0.13 nm after taking into account the instrument broadening. Thus the lasing threshold is reached at 20 μW. On the other hand, the emission turn-on time decreases rapidly with increasing pump power above the threshold. From both Fig. 1(b) and
Fig. 2, we can see that the response of the QD microdisk laser is very fast. At the pump power of 80 µW, the turn-on time is only 7.8 ps. Compared with the previous results of GaAs/AlGaAs QW microdisk lasers whose fastest response is about 100 ps, the speed of a microdisk laser has been greatly improved when QDs are used as the active media. For QW microdisk lasers, the speed of the laser is limited mainly by the carrier diffusion in the disk plane. However, in QD microdisk lasers, the carriers are confined within individual QDs so that the carrier diffusion effect is suppressed, leading to a much faster response of the lasers. In Fig. 2, below the lasing threshold, we also note that the turn-on time increases with the pump power. This increase results from the interplay of carrier injection, spontaneous emission, and stimulated emission as illustrated in Ref. 4. When the carrier injection pulse is short enough (e.g., 10 ps), the increase of the turn-on time is clearly present in our simulation result. However, for QW microdisk lasers, the carrier diffusion will broaden the carrier injection pulse and smear out the increase of the turn-on time near the lasing threshold. Therefore, this phenomenon is not observed experimentally for the QW microdisk lasers. While in the QD microdisk lasers, the suppression of the carrier diffusion makes this phenomenon rather easy to be observed, as shown in Fig. 2. After the threshold is reached, the response of the laser is determined mainly by the fast stimulated emission. With a further increase of the pump power, the stimulated emission rate increases, and thus the response of the laser becomes faster.

In the following, we will study the temperature dependence of the dynamics for QD microdisk lasers. We vary the sample temperature from 5 to 140 K. The lasing threshold increases with the temperature. Figure 3(a) depicts the turn-on time as a function of the pump power, which is normalized to the lasing threshold pump power $P_{th}$. The lines are a guide to the eyes. From Fig. 3(a), at the same pumping level (i.e., the same $P/P_{th}$), it can be seen that the turn-on time is shortened with increasing temperature. The temporal evolution of the microdisk emission at the same pumping level $P = 1.1P_{th}$ but at different temperatures are shown in Fig. 3(b). It is very clear that the response of the laser becomes faster as the temperature increases from 5 to 120 K. We believe this is induced by the faster carrier relaxation in the QDs at higher temperature. The enhanced Auger-like carrier–carrier scattering and longitudinal optical phonon scattering at higher temperature may account for the faster carrier relaxation in QDs. In QD microdisk lasers, the width of the carrier injection pulse is mainly determined by the carrier relaxation rate when the carrier diffusion is suppressed. The faster carrier relaxation will not only reduce the width of the carrier pump pulse, but also lead to a shorter delay time between the optical pump pulse and the carrier pump pulse. Thus, a shorter turn-on time results. Next, we will simulate how the turn-on time of the microdisk lasers depends on the width of the carrier pump pulse with the rate equation model.

The rate equations for a QD microcavity laser (neglecting the surface recombination) can be written as

$$\frac{dN}{dt} = -\Gamma S G(N) - \gamma B N^2 + P_{p}(t),$$

(1)
The gain coefficient $G$ represents the carrier density at the transparency point. In the dimensional carrier confinement in InAs/GaAs results in a larger optical gain.\(^9\) From the spectral linewidth of the WG dimension, we attribute the decay of spontaneous emission entirely to nonradiative recombination. Namely, we assume the nonradiative recombination time $\tau_{nr}$ is equal to the decay time of the spontaneous emission. We re-calculate the turn-on times for the pump pulse width $w$ of 10, 5, and 1 ps, taking the nonradiative recombination time $\tau_{nr}$ of 375, 250, and 220 ps, respectively. The calculated results are shown in Fig. 4(b). Except for the fact that the absolute values of the turn-on times decrease slightly, the overall feature is very similar to that in Fig. 4(a). Therefore, we conclude that the nonradiative recombination has minor contribution to the turn-on time of a QD microdisk laser.

Finally, we examine the effect of the nonradiative recombination on the turn-on time by adding a nonradiative decay term, $-N/\tau_{nr}$, to the right-hand side of Eq. (1). $N$ is the carrier density, and $\tau_{nr}$ is the nonradiative recombination time. By curve fitting the exponential decay of spontaneous emission intensity at the pump level of $P = 0.5 P_{th}$, the decay times at 5, 77, and 120 K are found to be 375, 250, and 220 ps, respectively. Such a short decay time is presently not well understood. It may originate from a large exciton oscillator strength for small QD, superradiance, or a fast nonradiative recombination. To estimate the maximum effect of the nonradiative recombination on the turn-on time of a QD microdisk laser, we attribute the decay of spontaneous emission entirely to nonradiative recombination. This work is supported by the National Science Foundation under Grant No. ECS-9800068.

\[^{1}\text{R. E. Slusher and U. Mohideen, in Optical Processes in Microcavities,}\]