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 $Al_{0.7}Ga_{0.3}As$, 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 $Al_{0.7}Ga_{0.3}As$ 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 $TE_{22,1}$, $TE_{17,2}$, and $TE_{21,1}$, 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 increase 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

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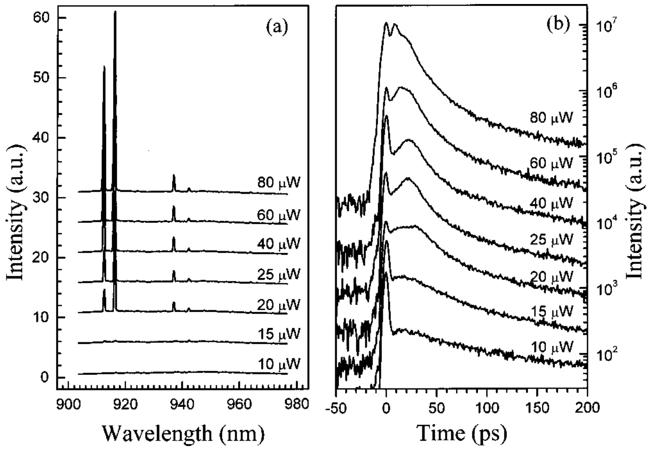

FIG. 1. (a) Experimentally observed time-integrated emission spectra, (b) temporal evolution of the microdisk emission at a temperature of 5 K. The incident pump powers are marked next to the curves, which are shifted vertically for clarity.

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,[4] 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.[4] 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.[4] 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.[4] While in the QD microdisk lasers, the suppression of the carrier diffusion

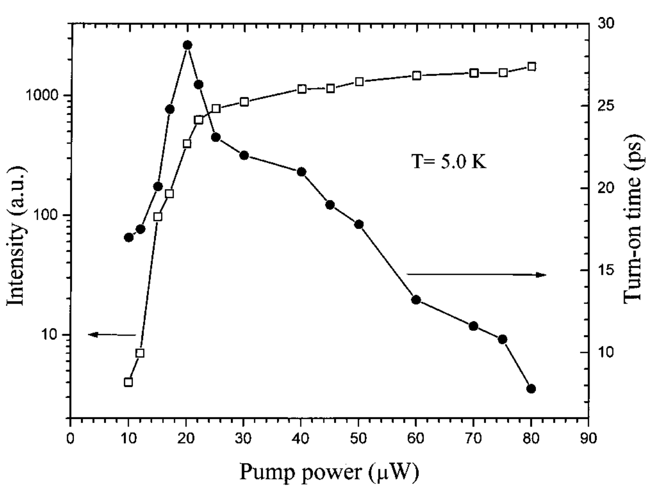

FIG. 2. The integrated emission intensity and the turn-on time as a function of the incident pump power at 5 K. The lines are a guide to the eyes.

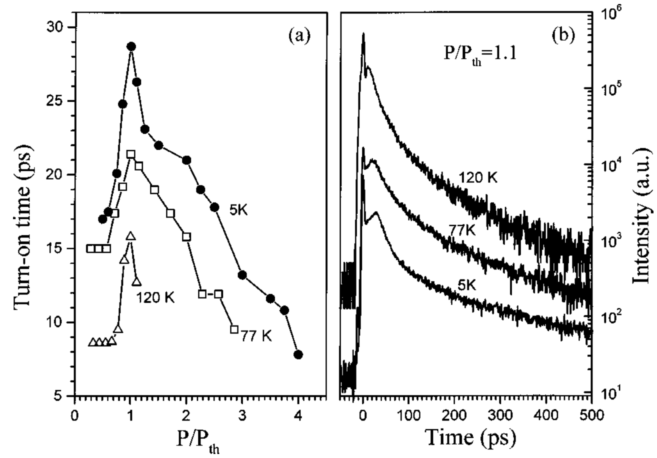

FIG. 3. (a) Experimentally observed turn-on time as a function of the pump power at temperatures of 5, 77, and 120 K. The pump power P is normalized to the lasing threshold pump power P_{th}. The lines are a guide to the eyes. (b) Temporal evolution of the microdisk emission at 5, 77, and 120 K. The pump power $P=1.1P_{th}$. The curves are shifted vertically for clarity.

make 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.[4] 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 P, which is normalized to the lasing threshold pump power P_{th}, at the temperatures of 5, 77, and 120 K. At 120 K, the lasing threshold is quite high and only one data point is obtained above the threshold. 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 $P=1.1\,P_{th}$ 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.[8] 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.[4] 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[1,2,4]

$$\frac{dN}{dt}=-\Gamma SG(N)-\gamma BN^2+P_p(t), \qquad (1)$$

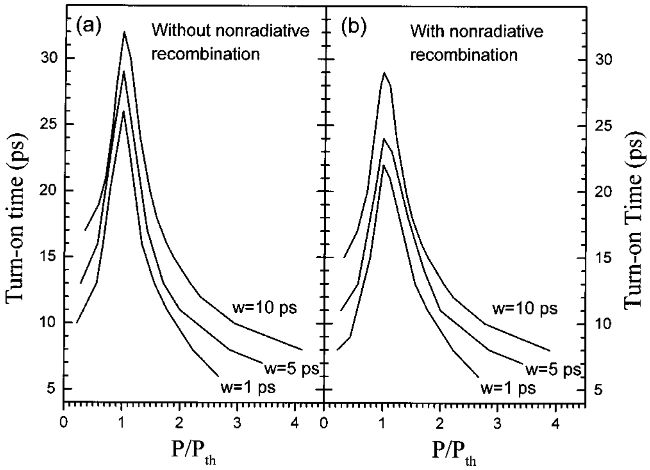

FIG. 4. Calculated turn-on time of a QD microdisk laser versus the normalized pump power P/P_{th} (a) without nonradiative recombination and (b) with nonradiative recombination. The FWHM of the carrier injection pulses is marked next to the curves.

$$\frac{dS}{dt}=\Gamma SG(N)+\gamma\beta BN^2-\frac{S}{\tau_p}, \tag{2}$$

where N denotes the carrier density in the active region, S the photon density in the laser mode, Γ the optical confinement factor, $G(N)$ the gain coefficient, B the spontaneous emission coefficient in a bulk semiconductor material, γ the enhancement factor of the spontaneous emission rate in a microcavity, $P_p(t)$ the carrier injection rate, β the spontaneous emission factor, and τ_p the photon lifetime. The carrier pulse is assumed to be Gaussian, i.e., $P_p(t)=P_0\times\exp(-2\sqrt{2}t/w)$, where w is the FWHM of the pulse. For our sample structure, we calculate $\Gamma=0.01$, $\gamma=1.0$, and $\beta=0.01$ for the lowest order TE mode in a 3 μm QD microdisk. The gain coefficient $G(N)=G_0(N-N_0)$, where N_0 represents the carrier density at the transparency point. In the simulation, we estimate $G_0\simeq1.0\times10^{-5}\,\mathrm{cm}^3/\mathrm{s}$, $N_0\simeq2.0\times10^{18}\,\mathrm{cm}^{-3}$, and $B\simeq1.0\times10^{-9}\,\mathrm{cm}^3/\mathrm{s}$. The value of G_0 is larger than that for a QW microdisk laser,[4] because the three-dimensional carrier confinement in InAs/GaAs results in a larger optical gain.[9] From the spectral linewidth of the WG mode near the transparency point, we estimate a photon lifetime (τ_p) of about 2 ps. Using these parameters, we solve the Eqs. (1) and (2) numerically for $N(t)$ and $S(t)$, and then deduce the turn-on time. With increasing temperature, it takes less time for the excited carriers to be captured by the QDs and subsequently relax to the lower energy levels in the QDs. Since the carrier relaxation time in InAs/GaAs QDs is between 1 and 10 ps,[8] we calculate the turn-on time when the pulse of carrier injection $P_p(t)$ has a FWHM of 10, 5, and 1 ps. The reduction of the carrier injection time corresponds to an increase of temperature. The simulated results are given in Fig. 4(a), which clearly shows that the turn-on time is shortened by decreasing the FWHM of the pump pulse at the same pumping level.

Finally, we examine the effect of the nonradiative recombination on the turn-on time by adding a nonradiative decay term, $-N/\tau_{\mathrm{nr}}$, to the right-hand side of Eq. (1). N is the carrier density, and τ_{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. Namely, we assume the nonradiative recombination time τ_{nr} is equal to the decay time of the spontaneous emission. We recalculate the turn-on times for the pump pulse width w of 10, 5, and 1 ps, taking the nonradiative recombination time τ_{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.

From Fig. 4, we can see that although our simulation model is simple, it explains qualitatively our experimental data. The decrease of the turn-on time with an increase of the temperature from 5 to 120 K may result from an enhanced carrier relaxation rate at a higher temperature. For a quantitative comparison with the experiment result, a more detailed theoretical study should be conducted, and many factors must be included (e.g., many-body effect in the QDs,[8] the variation of optical gain with the temperature,[9] more accurate parameters in Eqs. (1) and (2) for InAs/GaAs QDs, etc.). However, such theoretical study is beyond the scope of this letter.

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