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Quantum Dot Lasers Using High-Q Microdisk Cavities

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We report experimental observation of optically-pumped continuous-wave lasing from self-assembled quantum dots (QDs) embedded in high-quality factor (Q) microdisk laser structures. For large diameter (4.5 μm) microdisks containing InAs QDs, the emission spectra show simultaneous lasing on one to five well separated modes (Q = 10000–17000) in the wavelength range between 920 and 990 nm. For small diameter (2 μm) microdisks containing (In,Ga)As QDs, lasing occurs even when the estimated average number of QDs inside the cavity-mode volume is unity.

Semiconductor quantum dot (QD) microdisk structures combine small mode volume, high-Q values, and zero-dimensional electron density of states. These attributes offer the potential for low power, high speed optoelectronic devices. Recently, enhanced spontaneous emission efficiency [1] and optically pumped lasing [2, 3] from InAs QDs embedded in GaAs microdisks have been observed. In this paper, we report power-dependent PL measurements on single QDs and microdisk structures. The comparison of the data allows an estimation of the average number of QDs that couple to a mode.

Our samples were grown by molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. The microdisks consist of a disk and a pedestal area. One or two layers of (In,Ga)As self-assembled quantum dots (QD) were grown at the center of the 250 nm disk layer. The QD density of each array is 10^{11} cm^{-2}. Microdisks with diameters ranging from 1.5 to 6 μm have been fabricated. Details of the microdisk structure and the processing can be found in Ref. [3]. Furthermore, InAs QD samples with a gradient in the QD density ($\sim 10^8 - 10^{10}$ cm^{-2}) were fabricated. The layer structure, compositions and widths are given elsewhere [4]. Single QD PL measurements were performed in the low density area where the average distance between neighboring QDs was comparable to the spatial resolution (∼1.7 μm) of our microscope objective. The samples are mounted in a He gas flow cryostat and cooled to 6 K. Optical pumping is performed with a continuous-wave Ti:sapphire laser operating at 760 nm, generating free electron–hole pairs in the GaAs layer.

Figure 1 displays a typical PL spectrum for a 4.5 μm diameter disk under low excitation conditions (30 W/cm^2) in the range between 925 and 985 nm. Several sharp peaks, superimposed on a weak background signal are observed. The background corresponds to free QD PL, whereas the sharp peaks correspond to emission from QDs which cou-

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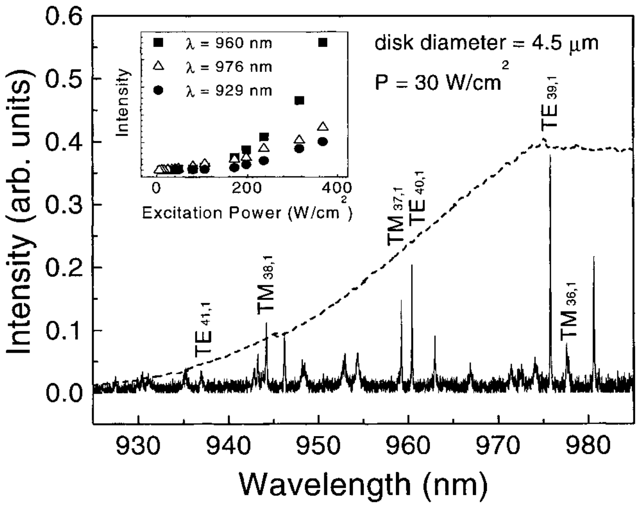

Fig. 1. PL spectrum of a 4.5 μm diameter microdisk in the range from 925–985 nm (solid line). For comparison the PL spectrum of the QDs of an unprocessed part of the wafer is also shown under similar excitation conditions (dashed line). Inset: Laser emission intensity versus incident pump power of a 4.5 μm diameter microdisk for three high-Q modes (960, 976, and 929 nm)

ple to microdisk modes. For comparison, Fig. 1 also shows the QD emission (dashed line, FWHM = 66 meV) of an unprocessed part of the wafer under equivalent conditions. The Q-values of the modes are typically above 10000 and for some modes they are limited by the resolution of our detection system ($Q \leq 17000$).

The modes of the microdisks can be approximated by the solution of the two-dimensional Helmholtz equation [5]. They are described by WGMs: $\psi(r) \sim J_m[(2\pi n_{\rm eff}/\lambda_{m,n})r]$, where J_m is the Bessel function of order m, n corresponds to the n-th zero of J_m, and $n_{\rm eff}$ is the effective refractive index. Due to the cylindrical symmetry a twofold degeneracy exists for $m > 1$. Our theoretical estimate of the WGMs with radial mode order $n = 1$ are also given in Fig. 1. It can be seen that these modes dominate the PL spectrum. However, higher radial number modes also contribute to the emission spectrum.

As the pump power increases, the peak intensity of the modes at 976, 960, 946, 929, and 927 nm increase drastically. The inset of Fig. 1 displays the intensity as a function of pump power for the 929, 960 and 976 nm modes. The observed nonlinear dependence suggests the onset of laser action. The threshold pump power densities for the five modes are in the range between 70 and 180 W/cm^2. We could not observe if there is a linewidth reduction above transparency, as the measurement is limited by the monochromator resolution (~0.05 nm).

Figure 2a shows the emitted intensity of the 909 nm mode of a 2 μm diameter disk as a function of the incident pump power density. A threshold behavior is also clearly seen for this mode. When the pump power density exceeds 20 and 30 W/cm^2, the emitted intensity increases much more rapidely with the pump power density. In that case, we were able to study the pump power dependence of the spectral linewidth of the mode which is plotted in Fig. 2b. Starting at linewidth of ~0.18 nm at 10 W/cm^2, the linewidth decreases to ~0.12 nm at threshold power. This indicates that Q is limited by QD absorption processes at low pump powers [6]. Above threshold (20–30 W/cm^2), we observe a further decrease of the linewidth until a value of ~0.095 nm is reached at 200 W/cm^2. The linewidth decrease above threshold density corresponds to an increase of temporal coherence. This narrowing is in agreement with recent observation on comparable structures [2].

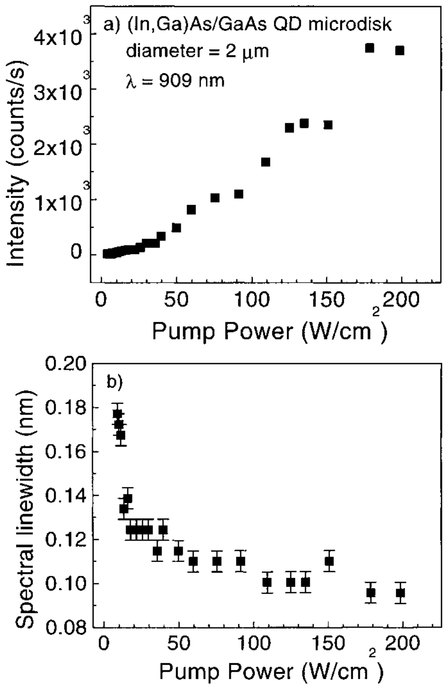

Fig. 2. a) Laser emission intensity and b) spectral linewidth versus incident pump power for a 2 μm diameter microdisk

The photoexcited carriers are localized in QDs with vastly different transition energies, resulting in an inhomogeneously broadened gain spectrum. All QDs whose homogeneously broadened linewidth (due to dephasing) overlap with a cavity mode, contribute to lasing of that mode [7]. Modes which couple to spatially isolated dots with transition-energy separations larger than the homogeneous broadening can start lasing simultaneously if the optical gain is above the lasing threshold. In order to study the spectral linewidth of the ground state transition and the onset of recombination processes from higher excited states, power-dependent PL spectra from single QDs have been recorded. Figure 3 shows a typical power-dependent PL spectra from a single InAs QD. At low excitation power (17 W/cm^2), a single sharp line (1.293 eV) due to single exciton recombination (X) is observed. With increas-

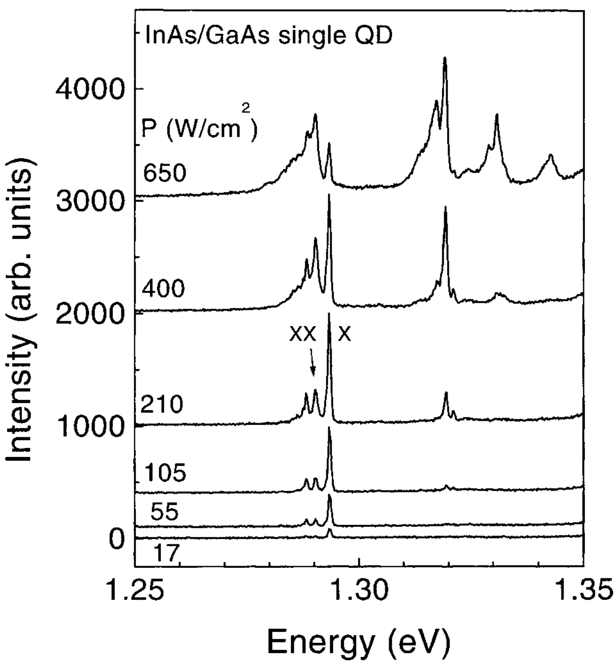

Fig. 3. Power dependent PL spectra from a single InAs QD. Contributions from the ground transition and from higher excited states are visible. The single exciton (X) and biexciton (XX) lines are labeled

ing excitation power two lines at 1.290 and at 1.288 eV appear below the single exciton line. The line at 1.290 eV originates from a biexciton decay (XX) whereas the line at 1.288 eV acquires contributions from the recombinations of higher multiexcitons [8, 9]. At still higher excitation powers (> 100 W/cm^2) we observe an increasing number of sharp lines below the single exciton line eventually merging into spectral bands at highest excitation power. At the same time, recombination lines at considerable higher energies (1.319, 1.331, 1.343 eV) successively appear in the spectrum. Under these excitation conditions, the QD is statistically occupied with three and more excitons and recombination from higher excited states occur [10]. It is important to note that high resolution PL spectra (not shown here) show that the single exciton linewidth is below 80 μeV (resolution limited) for excitation densities up to 400 W/cm^2. Furthermore, we want to point out that the single QD data have been obtained on the low-density QD area ($\sim 10^8$ cm^{-2}) of an unprocessed part of the wafer whereas the microdisk laser measurements have been carried out on high QD density samples ($\sim 10^{11}$ cm^{-2}). However, we will now use our single QD results to estimate the average number of QDs which contribute to the lasing of one mode.

The 4.5 μm microdisk contains two layers of InAs QDs with a total QD density of $\sim 2 \times 10^{11}$ cm^{-2}. Using the WGM mode area in the active disk plane [11], the linewidth of a typical mode at threshold of ~ 0.13 meV (Q = 10000), and the broad distribution of QD PL (~ 66 meV), we find the average number of QDs that couple with their ground state transition to a WGM mode to be ~ 8. We point out, however, that this average number in practice corresponds to a larger number of QDs that couple weakly to the WGM, either due to partial spectral or spatial overlap. Moreover, transitions from QDs with higher excited states might contribute to the emission at the estimated threshold power densities between 80 and 170 W/cm^2 (see Fig. 3).

The 2 μm microdisk contains a single layer of InGaAs QDs with a total QD density of $\sim 1 \times 10^{11}$ cm^{-2} with peak emission at ~ 910 nm. The threshold of the lasing mode shown in Fig. 2 is estimated to be ~ 20 W/cm^2. The linewidth of this mode at threshold ~ 0.16 meV (Q = 8000) indicates that the average number of QDs that couple to the lasing mode is unity and contributions from higher excited states are negligible at this excitation power density (see Fig. 3). This result indicates that it should be possible to realize a microdisk laser that contains a single QD.

In conclusion, we have fabricated record high-Q (≥ 17000) InAs/GaAs and InGaAs/GaAs QD microdisk structures. We have demonstrated optically-pumped cw-lasing from QD-based microdisk structures on one to five well separated modes in the wavelength range between 900 and 990 nm. For small diameter (2 μm) microdisks, lasing occurs even when the estimated average number of QDs inside the cavity-mode volume is unity.

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