Laser emission from quantum dots in microdisk structures

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We report optically pumped continuous-wave lasing from self-assembled InAs and InGaAs quantum dots (QDs) embedded in high-quality-factor microdisk laser structures. The microdisk emission spectra show lasing on 1–5 well separated modes in the wavelength range between 900 and 990 nm. The estimated threshold pump densities are between 20 and 200 W/cm^2. The lasing characteristics are discussed in terms of both inhomogeneously and homogeneously broadened QD transitions. [S0003-6951(00)04928-7]

Quantum dot (QD) microdisk structures are attractive for photonic devices since they combine small mode volume and zero dimensional electron density of states. These attributes offer the potential for ultralow threshold and high differential gain semiconductor lasers.[1] The gain spectrum of an ensemble of QDs—in contrast to a quantum well—is usually inhomogeneously broadened to a large extent since the carriers are localized in different dots, resulting in a system without a global Fermi function.[2] Microdisk lasers have only a certain number of high-quality factor (Q) whispering-gallery modes (WGM)[3] within a distinct spectral range. Typically only a few of these modes lie within the inhomogeneously broadened gain spectrum of the QDs. These features make the QD-microdisk system attractive for multi-wavelength lasing on distinct spectral modes over a wide spectral range.

In this letter, we report the observation of lasing in an optically pumped QD-microdisk system. In contrast to the previous results on QD lasers based on Fabry–Pérot cavities,[4,5] we obtain simultaneous lasing in five well separated modes in the wavelength range 920–990 nm.

Our samples were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The layer structure can be described as consisting of a disk area and a pedestal area. The disk area consists of 4 nm GaAs, 20 nm $Al_{0.3}Ga_{0.7}As$ barrier, 200 nm GaAs, 20 nm $Al_{0.3}Ga_{0.7}As$ barrier, and 4 nm GaAs cap. One or two layers of (In,Ga)As self-assembled QDs were grown at the center of the 200 nm GaAs layer. The QD density of each array is $10^{11}\,cm^{-2}$. The postlayer thickness used was either 0.5 or 1 μm of $Al_xGa_{1-x}As$, x ranging from 0.65 to 0.85, grown on top of an AlAs/GaAs buffer layer. Photolithography was used to define circles with diameters ranging from 1.5 to 6 μm. Either 1 μm thick photoresist or 50-nm-thick Ti was used to mask the substrate for the etching of the microdisk layer, using a HBr-based wet etchant. The etch extended into the AlGaAs post layer material. The etch solution used produced isotropic etching, with the disk diameter reduced (lateral etching) during the vertical etch into the material. After delineation of the microdisk feature, the pedestal layer is defined by etching in a dilute HF solution, which has a high selectivity in etching AlGaAs with high Al content in preference to GaAs. Scanning electron micrographs reveal the top disk layer to have a smooth, nonfaceted surface with an almost vertical etched profile.

The microdisks are mounted in a He gas flow cryostat and cooled to 6 K. Optical pumping is performed with a continuous-wave (cw) Ti-sapphire laser operating at 760 nm, generating free electron-hole pairs in the GaAs microdisk. The exciting light was focused to an approximately 30 μm diameter spot size on top of the microdisks. The emitted photoluminescence (PL) from the microdisks is collected at 90° with respect to the excitation direction in order to achieve a high collection efficiency.

Figure 1 displays a typical PL-spectrum for a 4.5 μm diameter disk under low excitation conditions (0.23 mW) 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 couple to microdisk modes. For comparison, Fig. 1 also shows the QD emission (dashed line, full width at half maximum=66 meV) of an unprocessed part of the wafer under equivalent conditions. The inset of Fig. 1 displays a high resolution PL spectrum of two WGMs at 959.2 and 960.4 nm, exhibiting linewidths of 0.07 and 0.057 nm, respectively. Intensity dependent measurements show a spectral

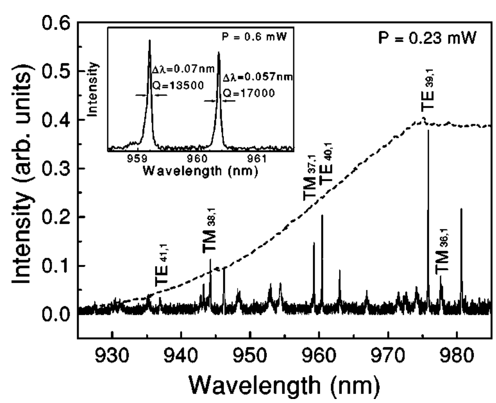

FIG. 1. PL spectrum of a 4.5 μm diameter microdisk in the range from 925 to 985 nm (solid line). For comparison the PL spectrum of the QDs of an unprocessed part of the wafer is also shown under similar excitation conditions (dashed line). Inset: High-resolution PL spectrum of two WQMs.

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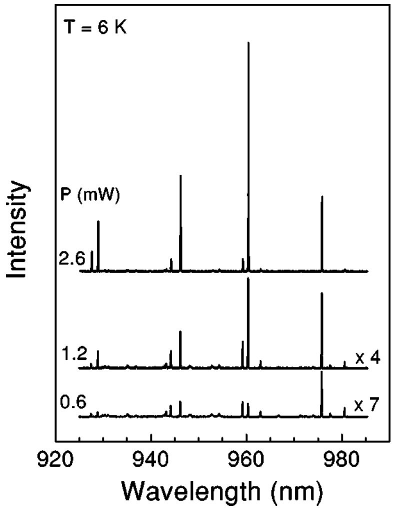

FIG. 2. Pump power dependence of the emission spectra of a 4.5 μm diameter microdisk.

narrowing of the WGMs with increasing excitation intensity, which indicates that Q is limited by QD absorption processes at low excitation intensities. This narrowing is in agreement with recent observations on comparable structures.[6] Therefore, we have determined the Q values near the transparency threshold and find typical Q values between 10 000 and 17 000 (resolution limit of our monochromator) for the high-Q modes.

The modes of the microdisks can be approximated by the solution of the two-dimensional Helmholtz equation.[7] They are described by WGMs: $\psi(r) \sim J_m[(2\pi n_{\mathrm{eff}}/\lambda_{m,n})r]$, where J_m is the Bessel function of order m,n corresponds to the nth zero of J_m, and n_{eff} is the effective refractive index. Due to the cylindrical symmetry a two-fold 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.

Figure 2 shows the pump-power dependence of the emission spectra of the 4.5 μm diameter microdisk for three different pump powers in the wavelength range from 925 to 985 nm. At low excitation power (0.6 mW) the long-wavelength high-Q mode at 976 nm dominates the emission spectrum. With increasing pump power, the intensity of the 960 nm mode increases most rapidly, dominating the emission spectrum. Figure 3 displays the intensity as a function of excitation power for (a) the 929 and 960 nm modes of the 4.5 μm diameter microdisk and (b) the 909 nm mode of a 2 μm diameter microdisk. The observed nonlinear dependence suggests the onset of laser action. The emission linewidth of the 2 μm diameter disk decreases with increasing excitation power from 0.15 nm at 0.03 mW to 0.1 nm at 1.4 mW. For the 4.5 μm diameter microdisk modes, we could not observe if there is a linewidth reduction above transparency, as the measurement is limited by the monochromator resolution ($\sim$0.05 nm). The threshold values (P_{th}) estimated from the laser emission dependence on pump power of the 4.5 μm diameter microdisk for the five lasing WGM are in the range 0.5–1.4 mW. The excitation-power dependence of a nonlasing mode ($\lambda=972$ nm) is shown in the inset of Fig. 3(a).

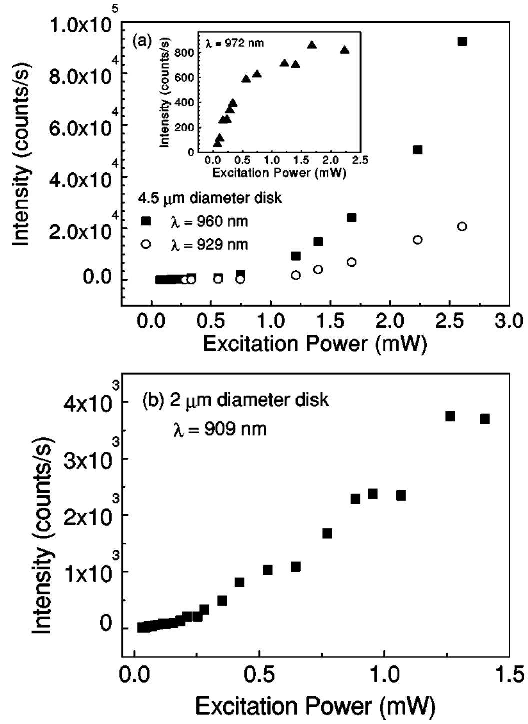

FIG. 3. (a) Laser emission intensity vs incident pump power of a 4.5 μm diameter microdisk for two high-Q modes (929 and 960 nm). Inset: PL intensity vs pump power for a nonlasing mode at 972 nm. (b) Laser emission intensity vs incident pump power for a 2 μm diameter microdisk.

After a linear increase in PL at low pump powers we observe a saturation at pump powers near P_{th}.

In order to explain our observations, we first note that 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.[5] 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.

First, we discuss the 4.5 μm microdisk results in detail: we find that the Q values of the nonlasing modes are typically below 10 000, whereas the Q values of the lasing modes are 14 000, 17 000, 12 000, 13 000, and 10 000 for the 976, 960, 946, 929, and 927 nm modes, respectively. This shows that lasing is only possible for modes with Q values$\geqslant$10000 in this sample. Taking the Q value at threshold density we can estimate the cavity losses from $\alpha=(2\pi n_{\mathrm{eff}})/(\lambda Q)$ (Ref. 6). The calculated α values for the lasing modes are between 12 and 22 cm^{-1}. At lower pump powers, lasing is only observed for the long-wavelength modes which lie in the center of the QD energy distribution and which possess Q's$\geqslant$14 000. At higher pump powers the short wavelength modes succesively start lasing. This might be related to the fact that higher energy levels with greater degeneracy are excited and contribute to the optical gain.

The mode at $\lambda=959.2$ nm was found to have a Q value of 13 500 (see Fig. 1). However, no lasing is observed even at the highest pump power. This can be understood if one considers the homogeneous broadening of the transitions and that a higher Q mode (960.4 nm, $Q=17000$) is spectrally separated by only 1.6 meV, spatially overlapping predominantly with the same QDs. First, the higher Q mode reaches threshold coupling to all QDs that have nonzero spectral overlap. Due to the homogeneous broadening of the gain the lower Q mode cannot reach threshold. We can use this result to conclude that the homogeneous broadening is at least in the order of 1.6 meV at threshold density for the 960.4 nm mode which is consistent with previous nonlinear absorption measurements.[9]

The 4.5 μm microdisk contains two layers of InAs QDs with a total QD density of $\sim 2 \times 10^{11}\,\mathrm{cm}^{-2}$. Using the WGM mode area in the active disk plane[8] and the broad distribution of QD PL ($\sim 66\,\mathrm{meV}$), we find the average number of QDs that couple 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. In particular, the homogeneous broadening of a QD ground state transition at a pump power density of $300\,\mathrm{W/cm}^2$ has been found to be on the order of 5 meV.[9] Using this value one can conclude that in average ~ 400 QDs contribute to the lasing of one mode at this power density.

The 2 μm microdisk contains a single layer of InGaAs QDs with a total QD density of $\sim 1 \times 10^{11}\,\mathrm{cm}^{-2}$ with peak emission at ~909 nm. The threshold of the lasing mode shown in Fig. 3(b) is estiamted to be 0.15 mW. The linewidth of this mode $\sim 0.16\,\mathrm{meV}$ ($Q = 8000$) indicates that the average number of QDs that couple to the lasing mode is unity. 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 ($\geqslant 17\,000$) InAs/GaAs and InGaAs/GaAs QD microdisk structures. We have demonstrated optically pumped cw-lasing from QD-based microdisk structures with estimated threshold pump densities between 20 and $200\,W/\mathrm{cm}^2$. The microdisk emission spectra show simultaneous lasing on 1–5 well separated modes in the wavelength range between 900 and 990 nm.

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