SHORT COMMUNICATION

High efficiency silicon nanodisk laser based on colloidal CdSe/ZnS QDs

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Abstract

Introduction: Using colloidal CdSe/ZnS quantum dots in the submicron-sized silicon disk cavity, we have developed a visible wavelength nanodisk laser that operates under extremely low threshold power at room temperature.

Methods: Time-resolved photoluminescence (PL) of QDs; nanodisk by e-beam lithography.

Results: Observation of lasing action at 594 nm wavelength for quantum dots on a nanodisk (750 nm in diameter) cavity and an ultra-low threshold of 2.8 μW.

Conclusion: From QD concentration dependence studies we achieved nearly sevenfold increase in spontaneous emission (SE) rate. We have achieved high efficient and high SE coupling rate in such a QD nanodisk laser.

Keywords: nanodisk; quantum dot; nanolaser; spontaneous emission; whispering galley mode

Chemical fabrication of colloidal quantum dots (QDs) is relatively inexpensive and more straightforward as compared to epitaxial methods. Due to their simple solution processing, high fluorescence quantum yields, room temperature operation, wavelength tunability, and other remarkable optical properties, QDs offer many potential applications. Because of their large absorption cross-section, QDs could be used in solar energy applications (1–4) as well. Since the first development in 1994, QD-LEDs (5–12) have offered great potentials in light emitting and display devices (13). However, for applications such as quantum information technology, single photon emission from a single QD (14–16) is essential, and in this context the exiton-photon coupling issue has attracted wide theoretical and experimental interest.

Spontaneous emission (SE) of an optical field strongly depends on its surrounding electromagnetic vacuum fields, which are called the photonic density of states or optical modes (17, 18). Therefore, it is possible to modify (enhance or reduce) the SE rates by manipulating optical modes. One of most popular methods to modify the SE rates is to couple light sources into the cavity modes. The behavior of this type of photon-atom interactions can be described by the Purcell effect (19, 20). The Purcell factor (Fp) is proportional to the ratio of the quality factor (Q) and the mode volume (V) according to the theoretical model, and can be determined experimentally by Fp = G_cavity/G_free, where G_cavity and G_free are the radiative decay rates with and without the coupling to the cavity modes. It can also be related to the SE coupling efficiency, which is often called the β factor defined as β = Fp/(Fp + γ), where γ represents the optical loss.

There are several studies for the coupling between colloidal QDs and microcavities (21–23). In this report, we present that a large Purcell factor and high coupling efficiency could be achieved based on colloidal CdSe/ZnS QDs coupled to the Si nanodisk. In addition, development and functioning of a Si nanodisk laser is demonstrated at a visible wavelength with a very low threshold power. Such demonstration is an important achievement for the progress of Si-based optoelectronic devices.
Results and discussion

Nanodisk cavities were implanted in a 100 nm thick Si layer on the top of a SOI (Silicon-On-Insulator) wafer. This air-Si-air structure would have a strong vertical optical confinement. Electron beam lithography (EBL) technology was used to define nanodisk patterns with polymethylmethacrylate (PMMA) resist. The patterns were then transferred through Si to silicon dioxide (SiO2) layer by using the inductive coupled plasma (ICP) etching system with the gas mixture of CF4 and Ar. The SiO2 layer served as a sacrificial layer during the selective wet etching with HF solution (10%). Colloidal CdSe/ZnS core shell quantum dots with various concentrations were spun-coated on the top of the Si nanodisk at the end of fabrication. Fig. 1(a) is a TEM image of CdSe/ZnS QDs on the Si surface. Each QD has approximately 6 nm in diameter as shown in Fig. 1(a). The absorption/photoluminescence (PL) spectrum from the CdSe/ZnS core shell quantum dots layer is shown in Fig. 1(b). The peak wavelength and the full width at half maximum (FWHM) of the spectrum are 585 nm and 23 nm, respectively.

To characterize the active device for the CdSe/ZnS QDs embedded on a silicon nanodisk cavity, a 467 nm diode laser under the pumped conditions with 100-picosseconds-pulsewidth and a 0.1% duty cycle was used. In order to overcome the absorption loss by the materials, a nano-sized resonant cavity was needed to sustain the population inversion condition. The lasing action of the QD nanodisk cavities was observed for the disk size larger than 750 nm in diameter. Shown in Fig. 2(a) and (b) are the SEM images of a silicon nanodisk cavity with 750 nm in diameter and 100 nm in thickness from the top view and angled view. The fabricated nanodisk has a smooth sidewall, leading to a low threshold power, and a high Q-value for such a compact laser. In addition, such a Si nanodisk cavity has an ultra small mode volume (V) leading to a large Purcell factor.

To evaluate the distribution of QDs on the surface of a nanodisk cavity, we employed an atomic force microscopic (AFM) technique. The AFM allows us to not only

![Fig. 1](image1.png)

**Fig. 1.** (a) Transmission electron microscope image of CdSe/ZnS core-shell QDs (average diameter = 6 nm). (b) Absorption (blue line) and PL (red line) spectra of CdSe/ZnS QDs.

![Fig. 2](image2.png)

**Fig. 2.** (a) Top view and (b) angled view for the scanning electron microscope images of silicon nanodisk cavity (disk diameter = 750 nm). (c) AFM image of QDs on the nanodisk surface at a density of ~7 QDs/μm².
probe the distribution of QDs on the Si wafer but also ensure QDs are not aggregated. The QDs at a different concentration were spun on the Si wafer have various distributions. At the lowest concentration, we obtained a low density \((30 \mu m^{-2})\) distribution as shown in Fig. 2(c).

Fig. 3(a) shows the lasing PL spectrum and the peak wavelength from the nanodisk. The lasing peak was observed at 594 nm wavelength. Fig. 3(b) shows the output optical power dependence on the incident pump power (L-L curve) of the lasing mode. The pump threshold power was observed at 2.8 \(\mu W\). The soft turning-on behavior in the L-L curve indicates the high fraction of SE coupled into the cavity mode, which could be described with the SE coupling factor \((\beta\text{-factor})\). The L-L curve plotted in a log-log scale was shown in the inset of Fig. 3(b). The SE coupling factor \((\beta\text{-factor})\) of this nanodisk laser was observed to be around 0.8.

In order to better understand the lasing mode of the cavity, we used the three-dimensional (3-D) finite-difference time-domain (FDTD) simulation method (24). The calculated spectrum for the nanodisk cavity is shown in Fig. 3(c) with blue-curve. There are several resonant whispering gallery modes (WGM) (25) within the QD gain region, but only two first-order WGMs exist, which are labeled \(M_{1,9}\) and \(M_{1,10}\). Other small peaks are from the higher-order WGMs, which usually have a lower quality factor \((Q)\) value. By comparing the lasing and calculated spectra, the lasing mode was verified to be the first-order WGM, \(M_{1,9}\) with the azimuthal number \(m = 9\). The inset in Fig. 3(b) shows the calculated mode profiles of \(M_{1,9}\) mode from the top view and from the side view. Based on the estimation of the overlap of QDs distribution and the mode profile on the nanodisk surface, the \(M_{1,9}\) lasing mode contains approximately seven coupled CdSe/ZnS QDs that support the optical gain for lasing.

To optimize the density of QDs for the nanodisk laser, we prepared solutions with different concentrations \((M)\) of CdSe/ZnS QDs, and spin-coated the solutions on silicon nanodisk cavities. The QD concentration was varied from \(5 \times 10^{-7}\) to \(5 \times 10^{-5}\) M. Fig. 4 shows the measured threshold power of a nanodisk laser coated with different QD concentrations. Since there will be more optical gain for the lasing mode in the nanodisk with increase in the density of QDs, the threshold power decreases as the QD concentration increases. However the threshold power increases for concentrations of QDs

![Fig. 3](image_url)

**Fig. 3.** (a) The lasing spectrum (594 nm) of a silicon nanodisk cavity (750 nm in diameter). (b) The L-L curve with a threshold power as low as 2.8 \(\mu W\). (c) The 3-D FDTD simulation for the Si nanodisk cavity. The calculated resonant spectrum of a 750 nm Si nanodisk (blue curve). Inset: calculated Hz profiles of \(M_{1,9}\) mode from the top and side views.

![Fig. 4](image_url)

**Fig. 4.** Threshold power of a Si nanodisk laser that was spin-coated with various concentrations of CdSe/ZnS QDs.
exceeding $10^{-5}$ M. This behavior is attributed to the lasing mode that requires more carriers for population inversion when the number of QDs further increases. The lowest threshold of the nanodisk laser was observed at $2.8$ µW with an optimized QD concentration at $5 \times 10^{-6}$ M.

Fig. 5(a) shows the $\beta$-factor (26) of a Si nanodisk laser with various concentrations of QDs that were extracted from the L-L curves in a log-log scale. The $\beta$-factor decreases from 0.8 to 0.05 as the QDs concentration increases, due to an increase of QDs population on the nanodisk surface leading to an increase of non-radiative recombination. We should also note that the volume of optical mode in this compact cavity is only $0.007 \mu m^3 (\sim 2(\lambda/\alpha)^3)$ that was obtained from the 3-D FDTD simulation. Therefore, only QDs around the circumference of a disk have better overlap with this WGM profile. Instead of supporting more gain, the extra QDs on the disk surface probably introduced more optical absorption.

The reduction of $\beta$-factor indicates that the SE coupling efficiency decreases. Therefore a reduction in the Purcell factor of the nanodisk cavity was expected. To verify this point and to validate the enhancement of SE rate in the nanodisk cavity, we carried out time-resolved PL measurements. Fig. 4(b) shows the time-resolved PL spectra measured from a nanodisk at a QDs concentration of $5 \times 10^{-6}$ M. The red spectrum was obtained non-cavity region, while the black spectrum was obtained from the edge of the nanodisk. The decay times of the emission from the non-cavity region and the cavity region are 4.5 ns and 0.65 ns, respectively. The Purcell factors could be determined experimentally from the decay time ratio $F_p = \Gamma_{\text{cavity}}/\Gamma_{\text{free}}$, where $\Gamma_{\text{cavity}}$ and $\Gamma_{\text{free}}$ are the radiative decay rates with and without coupling to cavity modes. From the measured results, we obtained nearly sevenfold enhancement in the SE rate for the QDs emission coupled to the designed optical modes of the nanodisk cavity. The relation between the $\beta$-factor and the Purcell factor ($F_p$) can be described as $\beta = F_p/(F_p + \gamma)$, here $\gamma$ represents the optical loss. Therefore, for a nanodisk cavity with a $5 \times 10^{-6}$ M concentration, the high $\beta$-factor 0.8 in Fig. 4(a) is in agreement with the Purcell factor from the decay time ratio of time-resolved PL spectra. Fig. 4(c) shows the measured decay time ratio (i.e. the Purcell factor) of a cavity with different QD concentrations. The PL decay time ratio decreases from 7 to 1.5 as the QDs concentration increases. This behavior of the ratio is in agreement with the decrease of $\beta$-factor in Fig. 4(a). These results indicate that at a high $\beta$-factor, high efficient lasing action from a Si nanodisk cavity can be obtained at a low CdSe/ZnS QDs concentration.

In summary, we have developed a nanodisk laser by depositing colloidal CdSe/ZnS QDs on a Si nanodisk. 

Fig. 5. (a) The spontaneous emission (SE) coupling factor ($\beta$) and the photon lifetime decay ratio from a silicon nanodisk laser with various QDs concentrations. (b) PL decay profiles of QDs on the silicon nanodisk: (red) in the non-cavity region and (black) in the cavity region. The decay times for the signal form the non-cavity region and from the cavity region are 4.5 ns and 0.65 ns, respectively. The lifetime ratio of the nanodisk cavity is around seven. (c) Lifetime versus various concentrations of QDs on the silicon nanodisk.
The lasing action at 594 nm was achieved with a ultra-low threshold of 2.8 $\mu$W with a low QDs concentration of $5 \times 10^{-6}$ M on a nanodisk having 750 nm diameter. The QD concentration dependence on threshold power was also investigated. Analysis of PL decay profiles showed a sevenfold enhancement in the SE rate due to an increase in the coupling between QDs emission and the lasing mode of the nanodisk cavity. Demonstration of QD-based nanodisk laser in this report shows potentials of colloidal semiconductor QDs for the development of nano-sized light sources.

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**Conflict of interest and funding**

There is no conflict of interest in the present study for any of the authors.

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