Monolithic integration of quantum dot containing microdisk microcavities coupled to air-suspended waveguides

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GaAs microdisk microcavities coupled to monolithic air-suspended waveguide structures are fabricated with out-of-plane light coupling achieved via the grating couplers monolithically integrated in the input and output ports. Photoluminescence signal of the whispering gallery modes is extracted from the grating couplers through the waveguide. Quality factors of modes are obtained through a transmission measurement with quality factors of up to 9500 and transmission depth of $\Delta T=35\%$. © 2009 American Institute of Physics. [DOI: 10.1063/1.3078522]

After the intensive development of dielectric microcavities containing semiconductor quantum dots (QDs), a variety of cavity quantum electrodynamics (QED) effects have been demonstrated, such as Purcell effect,1 Rabi splitting,2–4 or single photon emission in the strong coupling regime.2,5,6 Further improvements in the quality factors $Q$ are important, and indeed cavities with ultrahigh $Q$ factors $Q \sim 10^7$ can now be fabricated with III-V QDs embedded.7 Therefore, we can now imagine constructing a microphotonic circuit based on such high-$Q$ cavities to enable more complicated functionality to realize cavity QED based photonics quantum information devices and network.8 Such a circuit consists of arrays of cavities as information processing nodes and waveguide structures for interconnection. A quantum repeater protocol has been proposed based on such a system.9,10

Among the different types of microcavities, microdisk microcavities11,12 that support whispering gallery modes (WGM) have high $Q$ factors and small mode volumes $V$ and are therefore expected to play an important role in such applications. Evanescent coupling between a microdisk and a waveguide is demonstrated in a fiber taper system13 in a nonundercut silicon monolithic waveguide structure.14 In the fiber taper scheme, the strong coupling between the QD and the cavity is measured in the transmission spectrum.16 While fiber taper coupling has the advantage of the ability of modulating cavity-waveguide coupling easily by changing the gap size, fiber-carrying piezoactuators, a monolithic structure has the advantage of scalability and simple system preparation without integrating piezoactuators into cryostats.

In this letter, we developed high-$Q$ GaAs microdisk microcavities that are evanescently coupled to waveguide structures. Our device uses an integrated optics approach where all components of our photonic structure (cavity, waveguide, in/out-coupler) are fabricated monolithically. For the out-of-plane light coupling with the waveguide, grating couplers17 are fabricated. Compared to a side coupling scheme from the cleaved edges of wafer,14 this feature allows future dense integration as well as experimental convenience; no side windows are necessary and a standard cold-finger type cryostat with only a front window is usable without any modification. From the input port (width = 8 μm), the waveguide width is tapered down to 140 nm to support only the fundamental waveguide mode. A microdisk is placed in close proximity to the waveguide with a gap of about 100 nm, which is within the decay length of the evanescent wave of WGM. The waveguide width is tapered out to the output port (width = 4 μm). Here the input port size is designed to be larger than the beam focus size, while the output port size is comparable to the collection area of a microscope objective lens. The input and output ports also work as the base to support the air-suspended waveguide. The grating periodicity is calculated with the CAMFR software routine18 (a publicly available two-dimensional Maxwell equation solver) for 60° input from the normal direction and vertical output at design wavelength. For example, $\lambda_{\text{input}}=217$ nm and $\lambda_{\text{output}}=275$ nm for $\lambda_{\text{design}}=895$ nm. With this structure, we demonstrate the cavity mode photoluminescence (PL) extraction as well as cavity-waveguide interaction through a transmission measurement.

As for the wafer structure, the sample is grown on a semi-insulating GaAs (100) substrate by molecular beam epitaxy. After the GaAs buffer layer, a 1 μm sacrificial layer (Al0.8Ga0.2As) was grown. Then, the disk part was grown with a 10 nm GaAs cap layer, a 20 nm Al0.8Ga0.2As block layer, a 190 nm GaAs barrier layer, a 20 nm Al0.8Ga0.2As block layer, and a 10 nm GaAs cap layer. The block layers confine the carrier in the center part of the disk layer in the growth direction to avoid carrier trapping by the surface states. GaAs cap layers prevent surface oxidation after microdisk fabrication. The substrate temperature was 580 °C. The In0.3Ga0.7As QDs (Ref. 19) are grown in the center of the 190 nm GaAs barrier layer at a substrate temperature of 500 °C by depositing 8 ML of In0.3Ga0.7As. Under these conditions, large dots (70 nm base diameter and 10 nm height) are formed. The surface QD density is as small as 11 dots/μm². With the same QD, a large oscillator strength $f=50$ was measured in Ref. 2, which is five times larger than InAs QD and is important for strong QD-cavity mode coupling.

The fabrication process of the microdisk/waveguide structure is as follows. The grating patterns are written on the polymethylmethacrylate (PMMA) resist coated wafer by electron beam lithography, followed by electron cyclotron resonance (ECR) plasma etching with Ar/Cl₂ chemistry. Grating depth is 50 nm. After PMMA recoating, overlay electron beam lithography is performed to write the cavity/waveguide pattern. With area dose = 130 μC/cm², the
microdisk-waveguide gap becomes ~70 nm narrower than the design gap. Then, the pattern is covered with 50 nm nickel as the etch mask, and the structure is etched down to the substrate, again by ECR plasma with Ar/Cl₂ chemistry. The Ni etch mask is subsequently removed by Ni etchant at 50 °C for 60 s. Finally, the microdisk pedestal and air-suspended waveguide are formed by selectively etching the sacrificial layer with 5 vol % HF acid. The undercut etch rate is about 1.8 μm/min. Figure 1 shows the resulting structure. Surface stiction, attachment of the structure on the device pinhole that is placed on the microdisk in the charge-coupled device (CCD) image (collection area=2 μm). A signature of the waveguide-microdisk coupling is obtained by extracting the PL via the waveguide and the output coupler. For this measurement, the excitation source is a frequency doubled neodymium doped yttrium aluminum garnet laser at 532 nm such that the excitons are pumped into the GaAs/Al₃Ga₅As disk layer and relax into the ground state of In₀.₃Ga₀.₇As QD. At first, the signal is detected through a pinhole that is placed on the microdisk in the charge-coupled device (CCD) image (collection area=2 μm). Since the emission direction of ideal microdisks is in-plane, WGM scattered by the side-wall roughness toward the collection angle is detected with this configuration. At low excitation power (P_ex<10 μW), individual QD emission is resolved in the spectrum [Fig. 2(c)]. At higher excitation power, on the other hand, an “on disk” PL spectrum shown in Fig. 2(a) is obtained, which exhibits high-Q cavity modes (Q =3000–24 000) with the background of inhomogeneous QD emission. Next, the pinhole is shifted on top of the output grating coupler, and the “on grating” spectrum in Fig. 2(b) is obtained. This cavity mode PL is generated in the microdisk as WGM, out-coupled evanescently to the air-suspended waveguide, and emitted vertically by the grating coupler. This is justified because (1) the spectral position of the observed cavity modes matches with the previous spectrum and (2) no such a spectrum is observed with a broken waveguide. Although the output coupler is designed to couple the light out vertically at only one particular (design) wavelength, modes at a wide range of wavelengths are collected from the output coupler because a large NA microscope objective (NA=0.55) is used, collecting from a wide range of emission angles. Note that the cavity modes are more prominently seen in the on grating spectrum without the background inhomogeneous QD emission. Its absolute signal intensity, however, is just 5% of the on disk spectrum because of the phase-mismatch of the propagation constant between the waveguide mode and WGM, QD absorption in the monolithic waveguide and the output port, and low grating coupler efficiency of 3% from CAMFR simulation. For the same reason, individually resolved single QD peaks at low excitation power could not be detected in this output grating mode. Direct proof of the microdisk-waveguide coupling is obtained by a transmission measurement. The experimental configuration is shown in Fig. 3(c), where the light is input at 60° measured from the normal direction, back diffracted into the waveguide, and extracted in the vertical direction. Trans-

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mitted laser power, seen at the output grating coupler [Fig. 3(b)], is recorded through a pinhole placed on the output port. This oblique in-coupling/vertical out-coupling scheme is important to prevent the signal-to-noise ratio (S/N) degradation by the scattering of the input light. While the grating coupler can couple the light only at the design wavelength if the beam is collimated at fixed input angle, beam focusing makes a cone of input angles and the coupling bandwidth is broadened. A bandwidth of 2.3 nm (full width at half maximum) is obtained in this way with a $f=50$ mm input lens, which is wide enough to scan the high-$Q$ cavity modes whose linewidth is typically less than 0.1 nm. With this configuration, waveguide-cavity coupling would be reflected as a transmission dip.\textsuperscript{13–16} Indeed, such a dip is seen in a transmission spectrum as shown in Fig. 3(a) with the transmission depth of $\Delta T=35\%$. This spectrum is obtained by shifting the spectral position of the mode around fixed laser wavelength by changing temperature (25–50 K). The temperature dependence of the spectral position of WGM is measured from the PL measurement prior to the transmission measurement. The cavity $Q$ value obtained from the transmission measurement ($Q=9500$) matches to the PL measurement. The drop in the transmission intensity at larger detuning seen in Fig. 3(a) is due to the focus change during the temperature tuning. Although the microdisk-waveguide gap of the particular device is 140 nm—that is, larger than the evanescent decay length ($\sim 100$ nm)—and hence the system is likely to be in the undercoupling regime, this is a clear evidence of evanescent coupling. Compared to uncoupled microdisks with nominally same diameter, the $Q$ of the coupled microdisks is generally $\sim 10\%$ lower, which is another signature of the undercoupling [Fig. 2(d)]. Note that the actual gap, and hence evanescent coupling, might be changing during the temperature tuning. Accurate modeling would be needed to evaluate its effect by considering temperature induced mechanical strain.

In summary, we fabricated microdisks coupled with monolithic air-suspended waveguide structures where the light is coupled/extracted with grating couplers. The coupling is demonstrated by cavity mode PL extraction from the grating coupler through the waveguide, and the transmission measurement where $Q=9500$ is measured with transmission depth of $\Delta T=35\%$. These results show that evanescent coupling between the microdisk and waveguide is possible in this structure. Optimization of the waveguide width and the gap distance based on finite-difference time-domain simulation for better phase matching should be important, as performed in the Si microring structure,\textsuperscript{22} to obtain the critical coupling. For a sub-100 nm gap, optical proximity correction lithography needs to be utilized to prevent $Q$ factor reduction due to side wall roughening by the proximity effect. Once critical coupling is obtained, this system can be used as scalable integrated cavity QED based quantum information device.

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