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Fabrication and Optical Characterization of Photonic Crystal Nanocavities with Electrodes for Gate-Defined Quantum Dots

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Abstract

Optical coupling of gate-defined quantum dots (QDs) with photonic crystal (PhC) nanocavities provides a promising route towards efficient quantum spin-photon interface. As the first step towards this goal, we experimentally demonstrated PhC nanocavities with electrodes for gate-defined QDs. The electrodes which are designed to form single QDs were fabricated on two-dimensional PhC nanocavities with high position accuracy. Cavity mode spectra of the nanocavities were observed in micro-photoluminescence spectroscopy, demonstrating photon confinement in PhC nanocavities with electrodes for gate-defined QDs. The results are crucial for enhancing the interaction between gate-defined QDs and PhC nanocavities via their optical coupling.

1. Introduction

Quantum networks [1] composed of distant stationary matter qubits connected by flying photon qubits are expected to realize various quantum information (QI) applications. Quantum media conversion (QMC) which coherently transfer QI between electrons and photons is a key technology in such networks. To this end, quantum state transfer between electron spins and photon polarizations is a promising route. Since the proof of principles demonstrated using atoms or ions [2-4], interest has been also focused on solid-state systems for several advantages such as high scalability or stability. QMC between ensemble electron spins and photons were realized using quantum wells (QWs) [5]. Towards QMC at the single quantum level, various atom-like systems in solid have been studied. Self-assembled quantum dots (QDs) [6] or nitrogen vacancy (NV) centers in diamonds [7] have realized the QMC for single quanta. Also, angular momentum transfer from electrons to photons were observed in gate-defined QDs [8]. However, weak interaction between photons and the atom-like systems is an obstacle for efficient QMC.

Photonic crystal (PhC) nanocavities can be used for improvement of this conversion efficiency. Light confinement in small volumes on the order of cubic wavelength allows enhancement of the optical coupling between atom-like systems and nanocavities. Various cavity quantum electrodynamics phenomena have been observed using self-assembled QDs settled in PhC nanocavities [9, 10]. NV centers in diamonds are also studied towards their coupling with PhC nanocavities [11]. As for gate-defined QDs, which have shown remarkable advancement towards QI applications such as high scalability or sophisticated electrical spin manipulation and detection techniques [12-16], thereby, their optical coupling with PhC nanocavities is highly expected towards quantum spin-photon interface. Nonetheless, optical coupling of gate-defined QDs with PhC nanocavities have never been demonstrated. To this end, photon confinement in PhC nanocavities with the electrodes for gate-defined QDs will be an essential step.

In this study, we experimentally demonstrated PhC nanocavities with electrodes for gate-defined QDs. The electrodes which are designed to form single QDs are fabricated on the top surface of two-dimensional (2D) PhC nanocavities with high position accuracy. Cavity mode spectra of the nanocavities were observed by micro-photoluminescence (μ-PL) spectroscopy, demonstrating photon confinement in the PhC nanocavities despite the electrodes for the QDs located at the cavity region. This work is the crucial base for the optical coupling between gate-defined QDs and PhC nanocavities, leading towards efficient QMC using gate-defined QDs.

2. PhC nanocavities with electrodes for gate-defined QDs

Figure 1 shows a schematic of the studied PhC nanocavity on which electrodes for a gated-defined QD are placed. PhC

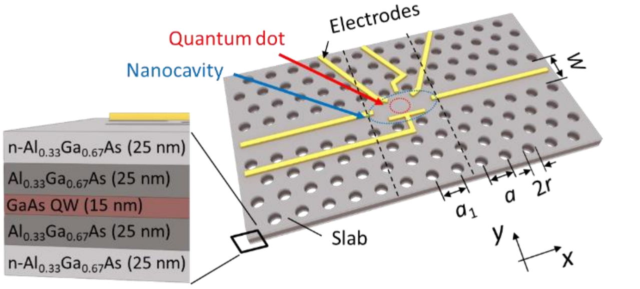

Fig. 1 Schematic of the studied PhC nanocavity with electrodes for a gate-defined QD. Bird's eye view is shown in the right image. Left image shows the cross-section of the slab layer.

structures are formed in a AlGaAs slab suspended in air. Circular holes of radius r are arrayed in the plane of the slab with the triangular lattice of period a. The series of holes horizontally arrayed at the middle are removed, forming a waveguide of width w. The PhC periods in between dashed lines in Fig. 1 are horizontally expanded to be a_1, which forms a double hetero PhC nanocavity at the center of the waveguide [17]. The 115 nm-thick slab layer includes a 15 nm-thick-GaAs layer at the middle as a QW sandwiched by 50 nm-thick-$Al_{0.33}Ga_{0.67}As$ layers. Top and bottom surfaces (25 nm-thickness for each) of the slab are n-doped with silicon. The electrodes which are designed to define single QDs at the nanocavity position are located on the slab as shown in Fig. 1. The PhC nanocavities with a=a_1/1.03=211 nm, r=0.26a and w=$\sqrt{3}a$-2r+40 nm support a x-polarized higher-order mode around the emission wavelength of the QW ($\lambda \sim 800$ nm). Also, the length between the closest hole edges becomes large enough for fabrication of the electrodes on the PhCs as well as for transportation of single electrons. Three-dimensional finite-difference time-domain (3D-FDTD) calculation shows that about 40 times optical absorption enhancement can be obtained within the nanocavity region at the wavelength of the nanocavity mode. Although the x-polarized mode is not directly applicable to QMC, photon confinement in PhC nanocavities with the electrodes can be confirmed for this mode, which is essential for the optical coupling between the gate-defined QDs and the PhC nanocavities.

3. Fabrication and optical characterization

For fabrication, we firstly prepared a substrate where AlGaAs sacrificial and the slab layers are sequentially grown by molecular beam epitaxy. The electrodes are fabricated by electron-beam (EB) deposition of gold using a mask patterned by EB lithography and a following lift-off process. The PhC patterns were drawn in the subsequent EB lithography while their relative positions to the electrodes were aligned with markers. The patterns are formed in the slab layer by reactive ion etching, then the slab is suspended in air by wet etching of sacrificial layer. Figure 2(a) is a scanning electron microscope (SEM) image of a fabricated sample. The position error between the electrode and the PhC was about 20 nm for this sample, showing successful fabrication.

For optical characterization, we measured x-polarized component of PL spectra shown in Fig. 2 (b) at room temperature for samples with different PhC periods from a = 213 nm to 229 nm. Two spectral peaks observed at the constant wave lengths of 827 nm and 857 nm regardless of a originates in spontaneous emission from the QWs. In addition to the two peaks, another peak is observed for each spectrum as shown by red arrows. The peak is red-shifted as a is increased, which is agreed with 3D-FDTD simulations and indicates that the peaks attribute to the resonant mode of the PhC nanocavities with the electrodes for gate-defined QDs.

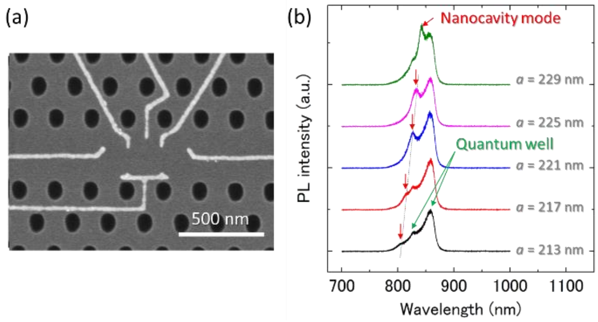

Fig. 2 (a) SEM image of a fabricated PhC nanocavity with electrodes for a gate-defined QD. (b) Room temperature μ-PL spectra for x-polarized light as a function of the PhC period a.

4. Conclusions

In conclusion, we experimentally demonstrated PhC nanocavities with electrodes for gate-defined QDs. The electrodes designed to form single QDs are fabricated on the 2D PhC nanocavities. Measured μ-PL spectra as a function of PhC periods clarified cavity modes of the PhC nanocavities, demonstrating photon confinement in PhC nanocavities with the electrodes for gate-defined QDs. This result is the crucial base for the future demonstration of optical coupling between gate-defined QDs and PhC nanocavities.

Acknowledgements

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