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Electro-mechanical control of *Q* factor in photonic crystal nanobeam cavity

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1. Introduction

Photonic crystal (PhC) nanocavity-single quantum dot (QD) coupled system is a fascinated platform to demonstrate cavity quantum electrodynamics (CQED) phenomena in solid state[1]. The emission properties from the coupled system are dramatically modified owing to CQED effects. A lot of studies in strong coupling regime using high *Q* cavities[2,3] have been reported. Coherent interaction between the QD and cavity photons in this regime is applicable to several quantum information devices. On the other hand, weak coupling regime in low *Q* cavity is also important for efficient light emission through the Purcell effect and to input(extract) photons to(from) the coupled system efficiently. Dynamical switching between these two regimes will lead to novel devices, in which both properties can be utilized on demand. One way to switch the coupling regime is control of *Q* factor of PhC nanocavities because *Q* is one of important parameters that determine the coupling regime of the system as discussed above.

Q-factor control has been examined in 2D PhC nanocavities by using local refractive index modification induced by pulse-laser illumination[4,5]. Micro electro mechanical system (MEMS) also provides another route to control optical properties of PhC[6]. In this study, in order to realize *Q* control, we combined a MEMS structure with 1D PhC nanocavity, called PhC nanobeam cavity[7]. This cavity structure receives much attention not only as a new platform of QD-CQED experiments[8] and but also as a movable nanocavity due to its thin and light properties. By changing the distance between two PhC nanobeam cavities using electrostatic force, tunable laser[9] and filter[10] have been demonstrated. These works mainly intended to enhance the tuning range of cavity wavelength. However, for the CQED applications, controlling *Q* with a small wavelength shift is essentially important.

Here, we report a design of electro-mechanically controllable nanocavity and the first demonstration on control of cavity *Q* of PhC nanobeam cavity by electro-mechanical manner. Continuous change in *Q* from 1,300 to 1,900 with an increase of applied voltage was observed by low temperature PL measurement.

2. Design and fabrication

Fig. 1(a) schematically illustrates our device structure. The device consists of a PhC nanobeam cavity coupled with a neaby nanobeam waveguide. Width and thickness of both the cavity and the waveguide are 345 nm and 130 nm, respectively. The initial gap distance between the cavity and the waveguide is set to 100 nm. The distance is controlled by electrostatic force between the metal electrodes (See the caption of Fig. 1). PhC nanobeam cavity consists of periodically arrayed air-holes and a parabolic modulation of hole distances in 5 nearest neighbors. Detail of design of PhC nanobeam cavity is shown in our previous report[8]. At the center of the waveguide, a 30 nm-length comb structure is introduced to increase the cavity-waveguide coupling, which increases the tuning range of cavity *Q*.

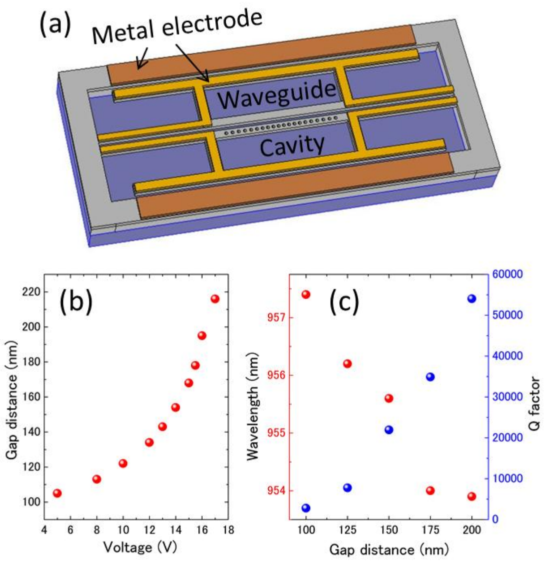

Fig. 1 (a) Schematic of an electro mechanically controllable PhC nanobeam cavity. Voltage is applied between metal electrodes (yellow and sand). (b) Calculated gap distance as a function of applied voltage. (c) Calculated gap-distance dependences of *Q* factor and resonant wavelength.

We estimate the tunable range of mechanical displacement and *Q* factor of the fundamental cavity mode by finite element method and finite difference time domain method in the structure. Fig. 1 (b) shows the applied voltage dependence of gap distance. Displacement of 100 nm is achieved at an applied voltage of 16 V. This displacement increased the cavity *Q* factor from 2,700 to 54,000, shown in Fig. 1 (c). These numerical simulations indicate that *Q* factor can be controlled in the range over one order of magnitude. Simultaneously, the cavity mode wavelength is blue shifted. This is undesirable effect in CQED experiments. However, this shift can be compensated by using a gas deposition technique[11].

We fabricated the designed structure by precisely controlled dry etching and metal deposition techniques. First, a 130-nm-GaAs slab containing InGaAs QDs layer at the middle was grown by molecular beam epitaxy on GaAs substrate with 1-μm-$Al_{0.7}Ga_{0.3}As$ sacrificial layer. The areal density of QDs is on the order of 10^9 cm^{-2} and the QDs emission ranged from 920 nm to 970 nm. All structures were patterned by electron beam lithography. After forming the cavity and waveguide structures by dry etching, metal electrodes consist of 5-nm-Ti and 120-nm-Au were deposited by electron beam evaporator. Finally, cavities and waveguides were released from the substrate by hydrofluoric acid wet etching to dissolve sacrificial layer. A typical scanning electron microscope (SEM) image of the fabricated device is shown in Fig. 2 (a).

3. μ-Photoluminescence Characterization

The fabricated PhC nanobeam cavities were measured by micro photoluminescence (μ-PL) experiments with applied voltage at low temperature (8K). First, we confirmed

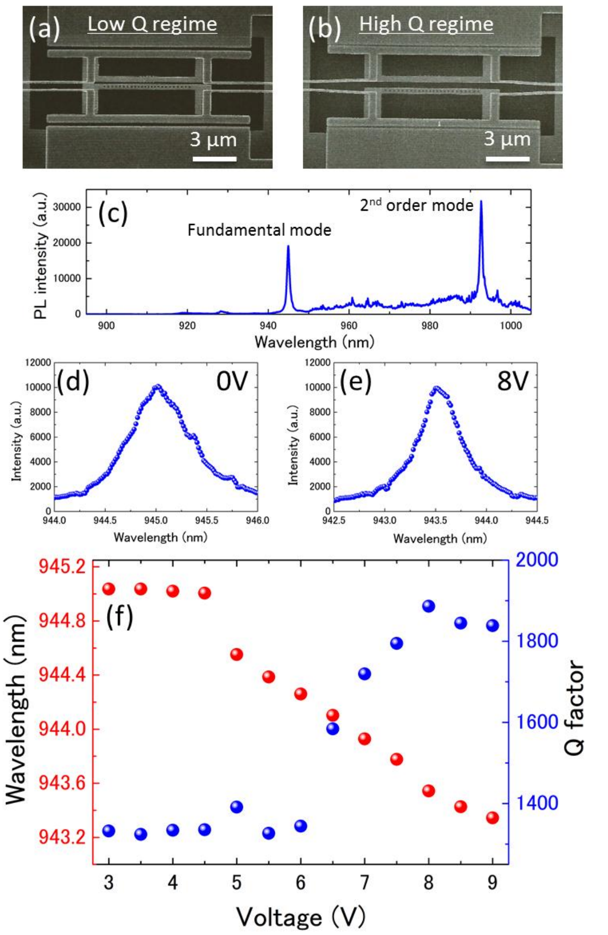

Fig. 2 SEM images of a fabricated structure before (a) and after (b) applying high voltage. (c) μ-PL spectrum from PhC nanobeam cavity at 0V. PL spectra at around the fundamental cavity mode without voltage(d) and at 8 V(e). (f) *Q* factor and resonant wavelength dependence vs. applied voltage.

the mechanical displacement of the structures by applying high voltage (> 20 V). Once a high voltage was applied, the metal electrodes stick each other. The structure did not go back to the original one after removing the voltage. The SEM images of before and after applying voltage are shown in Fig. 2 (a) and (b), respectively. The PhC nanobeam cavity and the waveguide are clearly displaced after the voltage application due to the electrostatic force.

We investigated the *Q* factor dependence by measuring PL spectra from a cavity mode. The sample was excited by a HeNe laser at a power of 2 μW on the sample surface. Two strong peaks originating from fundamental and 2nd order cavity modes were observed (Fig. 2 (c)). We focused our attention on the fundamental cavity mode and measured PL spectra at various applied voltages. Fig. 2 (d) and (e) show PL spectra from the same cavity at 0 V and 8 V. The *Q* factor and resonant wavelength of the cavity mode were extracted by fitting them with Lorenz functions. The voltage dependence of measured *Q* factor and wavelength are plotted in Fig. 2 (f). A clear enhancement of *Q* factor with a blue shift of resonant wavelength is observed. The maximum *Q* factor of 1,900 was achieved at 8 V. These behaviors of *Q* factor and resonant wavelength consist with our numerical simulations. The observed tuning range of Q is much smaller than the calculated one. We believe further process optimizations will increase maximum *Q* factor and will broaden tuning range.

4. Conclusion

We designed an electro-mechanically controllable PhC nanobeam cavity showing a tuning range of *Q* over one order of magnitude with a relatively small wavelength shift. Continuous change in *Q* factor from 1,300 to 1,900 was observed as an applied voltage increased. This is the first experimental demonstration of *Q*-control of PhC nanobeam cavity in electro-mechanical way. Further process optimization will make it possible to increase the tuning range of *Q* as predicted in our numerical simulations.

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