E-8-02 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp321-322

Design of semiconductor Bull's-eye optical cavity for high-efficiency quantum media conversion using a gate-defined quantum dot

S. -M. Ji[1], T. Tajiri[2], H. Kiyama[3], A. Oiwa[3] and S. Iwamoto[1]

[1] Research Center for Advanced Science and Technology, the University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
Phone: +81-3-5452-6291 E-mail: smji@iis.u-tokyo.ac.jp
[2] University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
[3] The Institute of Scientific and Industrial Research, Osaka University
8-1 Mihogaoka, Ibaraki-shi, Osaka 567-0047, Japan

Abstract

It is crucial to enhance the coupling between a photon with an arbitrary polarization state and an electron spin in a gate-defined quantum dot (QD) for realizing efficient quantum media conversion using a gate-defined QDs. Here, we report a design of optical cavity capable of incorporating a gate-defined QD within and enhancing the absorption equally for photons with arbitrary polarized states. The designed cavity base on a Bull's-eye structure supports degenerate resonant modes with orthogonal polarizations. Numerical analysis shows that the absorption of a QD can be enhanced more than 400 times at the resonant wavelength. The results pave the way for efficient quantum interface between photons and electron spins in a gate-defined QD.

1. Introduction

Quantum media conversion (QMC) between stationary qubits and flying photon qubits is one of the key technologies for entanglement distribution over distinct quantum nodes [1]. So far, experimental demonstrations of QMC with a trapped atom [2] or ion [3], a nitrogen vacancy center in diamond [4], and a semiconductor self-quantum dot (QD) [5] have been reported. Gate-defined QDs are another promising platform for QMC. Electron spin qubits in the QDs can be manipulated electrically with high precision. Besides, the QDs can be fabricated deterministically with high degree of scalability [6]. Spin-selected excitation of an electron in a gate-defined QD by a single photon has been demonstrated [7]. However, the absorption efficiency of photons was limited to ~10^{-4} due to the weak interaction between QDs and incoming photons [7]. Thus, significant improvement of the absorption efficiency is strongly demanded for realizing efficient QMC based on a gate-defined QD by fully utilizing its advantages.

A promising approach to enhance the interaction between gate-defined QDs and photons is to introduce optical cavities. We have fabricated a two-dimensional photonic crystal (PhC) nanocavity with electrodes for a gate-defined QD and have observed cavity modes [8]. Although this is an important progress towards an efficient QMC with a gate-defined QD, these resonant modes only coupled with photons with a linearly polarized state because of the elongated cavity structure [8]. Since QMC requires an arbitrary polarization state of photon to be converted to a corresponding electron spin state, a novel design of optical cavity capable of enhancing the absorption equally for photons with arbitrary polarized states and incorporating a gate-defined QD within is required.

In this study, we design a cavity with a Bull's eye structure, in which electrodes forming a gate-defined QD at the center are introduced. The structure still preserves C_{4v} symmetry with respect to the cavity center, allowing the cavity to support doubly degenerate resonant modes with orthogonally polarized main electric field. Numerical analysis shows that this cavity can enhance the photon absorption by the QD with a factor of more than 400 in the equal magnitude for incident light with orthogonal polarizations. This result indicates that incoming photons with any polarization states can equally couple with the cavity by exciting a corresponding linear combination of the modes.

2. Design and numerical analysis of Bull's eye cavity with electrodes

The studied cavity structure is shown in Fig. 1(a). The cavity is composed of a 340-nm-diameter circular disk at the center and 6-period Bragg grating surrounding the disk. The period Λ and air-gap filing factor for the grating are $\Lambda = m \times 170$ nm and 0.4 respectively, where m is a diffraction order of the grating. The grating is formed in an air-suspended 165-nm-thick semiconductor slab, which consists of a 15-nm-thick GaAs quantum well (QW) sandwiched by two 75-nm-thick $Al_{0.33}Ga_{0.67}As$ barriers. The grating is partially filled with a width of W, along the orthogonal two straight lines which are crossed at the center of the cavity. On the space, four gold electrodes with a width W_e of 36 nm and a thickness of 24 nm (yellow lines in Fig. 1(a)) are located to form a gate-defined QD at the center of the cavity. All numerical results discussed below were obtained by using 3D-finite difference time domain method.

This cavity supports degenerated resonant modes around the light emission wavelength of QW (~800 nm). Spatial field distributions of the main electric field component of the degenerated modes, A and B, for the structure of $m = 1$, $W = 100$ nm are shown in Fig. 1(b). Since the structure has C_{4v} symmetry, the field distributions of the modes are equivalent to each other for 90 degrees rotation. Figure 1 (c) shows the spectra of the absorbed power within the 42.5 nm x 42.5 nm

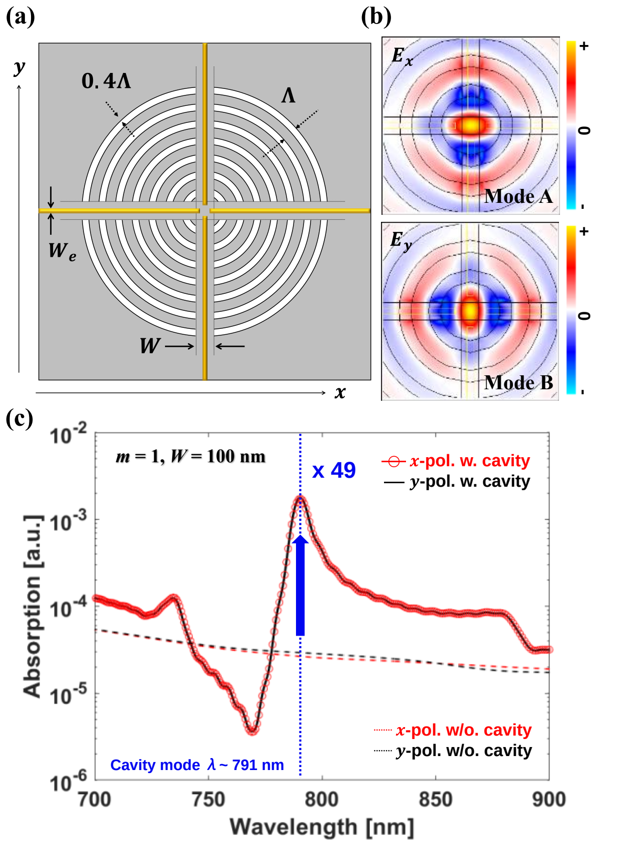

Fig. 1 (a) Bull's eye cavity structure with electrodes for a gate-defined QD. The cavity structure is formed in an air-suspended slab on which gold electrodes are placed. (b) x-y cross-sectional distributions of dominant electric field components for the degenerated modes, A and B. (c) Absorption spectra for *x*- and *y*-polarized light with and without the cavity structure.

area in the QW, which is a typical lateral size of a gate-defined QD, for *x*- and *y*-polarized vertically incoming Gaussian beam. The spectra for both polarizations are almost overlapped because of the structural symmetry. The absorption at the resonant wavelength is enhanced by a factor of 49 times compared with that of without the cavity structure.

Figure 2 shows the absorption enhancement ratio at the resonant wavelength as a function of W for m = 1 and 2. The absorption enhancement ratio for m = 1 can be further increased as W decreases, which is mainly attributed to the smaller cavity mode volume at smaller Ws. However, considering the fabrication tolerance of electrodes [8], the structures with such a small W (< 75 nm) are difficult to realize in experiments. On the other hand, for the structures with m = 2, the enhancement ratio is larger than that for m = 1 over the range of W investigated. The absorption spectra for the cavity with m = 2 and W = 100 nm, which is accessible in experiment, is shown in Fig. 3. Similar to the case of m = 1, the absorption spectra for m = 2 are almost same for both polarizations. The absorption at the cavity resonance is 410 times stronger than that without the cavity structure. The origin for larger absorption in the cavities with m = 2 is the increase of the coupling efficiency with the incident light due to the nature of second order diffraction of the grating.

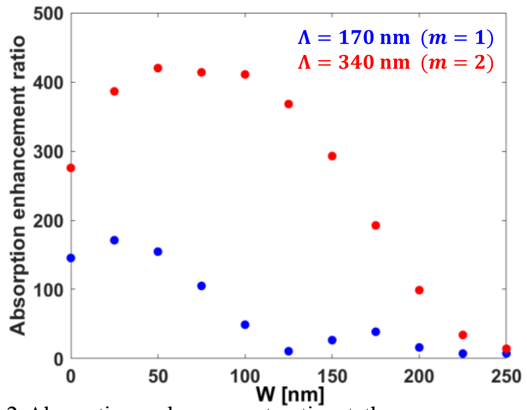

Fig. 2 Absorption enhancement ratio at the resonance wavelength, for the structures with m = 1 and 2, as a function of W

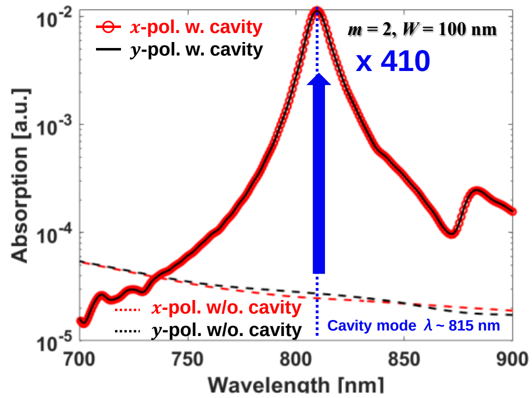

Fig. 3 Absorption spectra for the cavity with m = 2 and W = 100 nm. Dashed curves are the absorption spectra without the cavity.

3. Conclusions

In conclusion, we designed a Bull's eye cavity capable of introducing a gate-defined QD. The cavity supports degenerate cavity modes with equivalent field distributions for orthogonal polarizations, which potentially allows incoming photons to couple with the cavity regardless of their polarization. We also found that the second-order grating is useful for significantly enhancing the photon absorption in a gate-defined QD. Our numerical simulations demonstrate that the designed cavity can enhance the absorption for incident light with orthogonal polarizations equally more than 400 times compared with the absorption without the cavity structure. These results indicate that the Bull's eye cavity is a promising optical cavity structure for efficient QMC using a gate-defined QD.

Acknowledgements

This work is supported by JST, CREST JPMJCR15N2.

References

[1] H. J. Kimble, *Nature* **453**, 19 (2008).
[2] T. Wilk *et al.*, *Science* **317**, 488 (2007).
[3] B. B. Blinov *et al.*, *Nature* **428**, 153 (2004).
[4] E. Togan *et al.*, *Nature* **466**, 730 (2010).
[5] W. B. Gao *et al.*, *Nature* **491**, 426 (2012).
[6] T. Ito *et al.*, *Sci. Rep.* **6**, 39113 (2016).
[7] T. Fujita *et al.*, *Nature Comm.* **10**, 2991, (2019).
[8] T. Tajiri *et al.*, *Jpn. J. Appl. Phys.* **59**, SGGI05 (2020).