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2D Semiconductor-Based Photonic Crystals for Nano-Integrated Optics

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1. Introduction

Photonic crystals (PCs) have been extensively studied in the last decade due to their potential applications in optoelectronic devices [1]. III-V compound semiconductor-based two-dimensional (2D) PC slabs are promising for ultra-small photonic integrated circuits (PICs) with light sources, optical switches and waveguide components [2]. In particular, a 2D-PC-based symmetric Mach-Zehnder (SMZ) type ultrafast all-optical switch with buried quantum dots (QDs) as optical nonlinear (ONL) materials is currently our promising target (hereafter referred to simply as a PC-SMZ) [3]. In this paper, we show a device concept and key issues for implementation of this device. We also show recent results and future perspective on our PC and QD technologies for this device.

2. Concept of Ultra-Small All-Optical Switch: PC-SMZ

Conventional SMZ-type all-optical switches with ONL materials have already been demonstrated to show excellent ultra-fast switching characteristics, the speeds of which are not restricted to the carrier lifetime of ONL materials [4]. Further development is going on for reducing an optical switching energy (OSE). The PC-SMZ is promising for an advanced SMZ switch [3], because a careful design of several PC-based defect waveguides (D-WGs) has a potential ability to further reduce the OSE, thus providing an ultra-small and ultra-fast photonic switch. Figure 1 shows a schematic picture of the PC-SMZ. Owing to an ONL effect, refractive indices (n_{dot}) of the site-controlled QDs (SC-QDs), selectively embedded in the two arms, are modified by two control pulses whose time slots differ by a delay time generated by an integrated PC-based delay element. At a switch-on time, two arms are designed so that the π-phase-shift occurs between the two signal pulses due to the n_{dot} difference, similarly to the principle of the conventional SMZ switch.

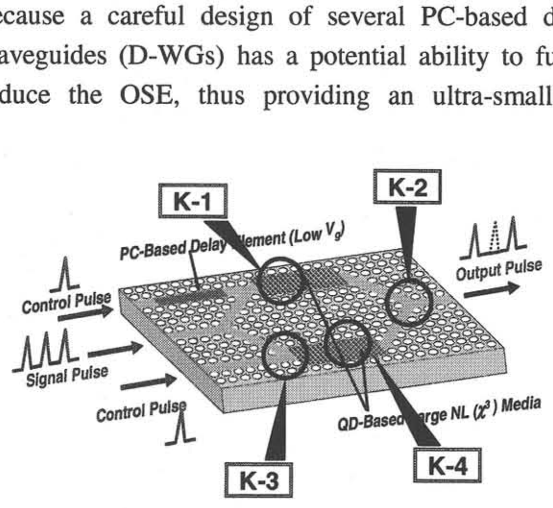

Fig. 1 Schematic diagram of the PC-SMZ and key issues (K-1 to K-4) for development.

3. Key Issues for PC-SMZ Technologies

Due to the structural difference between the conventional SMZ and PC-SMZ, design of the PC-SMZ requires several key issues, as shown by K-1 to K-4 in Fig. 1. For reduction of the OSE, usage of a low group-velocity (V_g) in a QD-buried D-WG is effective for enhancing the n_{dot}-induced phase shift [5,6]. In general, a PC-based high-Q cavity easily causes the low V_g. However, the spectral-peak width of such a cavity is not wide enough as compared with the amount of the peak-shift due to the n_{dot} change. So, the first key issue is a design of the D-WG in the arm (K-1 in Fig. 1) for maintaining the V_g low enough and the peak width large enough for achieving the required phase shift. The second key issue is a design of a junction waveguide (K-2). At the junction, an optical beam in one arm should not propagate into another arm for preventing unnecessary ring modes. The third key issue is a bend (K-3) whose reflectivity is minimized for preventing a Fabry-Perot resonance between the two bends in the arms. The fourth key issue is a nano-fabrication technology for SC-QDs in the arms (K-4).

4. PC-Based Defect Waveguide Technologies

As a basic platform for the PC-SMZ, we have developed straight, 60°-bend, and Y-branch D-WGs in the 2D-PC slab and reported the resulting band structures and transmission spectra based on both theoretical and

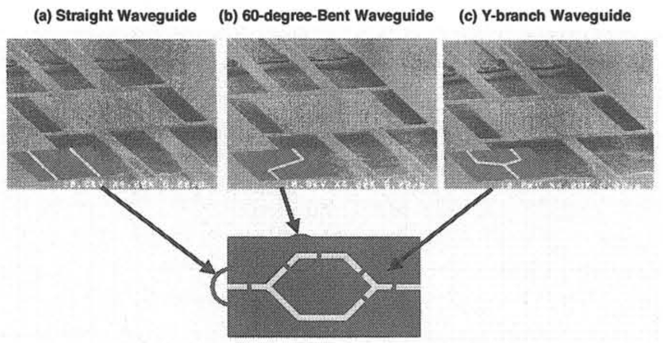

Fig. 2 SEM photographs of air-bridge structures with straight, 60°-bend, and Y-branch waveguides.

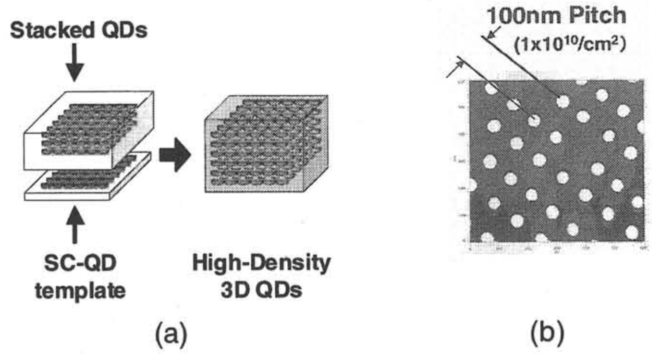

Fig. 3 (a) Schematic diagram of fabricating high-density QDs. (b) STM image of high-density SC-QDs fabricated using a nano-probe-assisted process.

experimental analyses [7-10]. Figure 2 shows SEM images of air-bridge type 2D-PC slabs with D-WGs fabricated using electron-beam lithography, dry etching and selective wet-etching [3]. Schematic waveguide patterns are inserted in each photo for reference. Each D-WG is constructed with a line of missing air-hole pattern. A 250-nm-thick $Al_{0.1}Ga_{0.9}As$ core layer was MBE grown on top of a 2-μm-thick $Al_{0.8}Ga_{0.2}As$ clad layer on a GaAs substrate. Measured transmission spectra of these D-WGs are in good agreement with calculated ones [8-10].

5. Site-Controlled Quantum Dot Technology

Spatially selective growth of QDs only in the arms of the PC-SMZ is achieved by fabricating a template with high-density SC-QDs by means of a nano-probe-assisted technique [11], as shown schematically in Fig. 3 (a). Fabrication of a high-density SC-QD template is followed by stack of QDs in the core layer by using a conventional strain-induced, vertically self-aligned growth method. For achieving a large ONL region in the PC-SMZ, size fluctuations of both SC-QDs and stacked QDs should be minimized to less than 30meV in a PL line width. Figure 3 (b) shows an STM image of the high-density SC-QDs fabricated using an STM-assisted process. Currently, QD array pitches of 50 to 100nm, corresponding to densities of 1 to 4 x $10^{10}/cm^2$, and the PL line width of around 30meV have been achieved.

6. Conclusion

We have developed design and fabrication technologies of 2D-PC waveguides, and selective growth technology of SC-QDs as ONL materials for implementation of the PC-SMZ. These technologies are promising not only for the SMZ devices but also for other integrated ultra-small planar light wave circuits.

Acknowledgement

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