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Optical-Nonlinearity-Induced Phase Shift via Selective Area Grown InAs-QDs in a Photonic Crystal Waveguide

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1. Introduction

We have so far developed ultrasmall all-optical switch device based on photonic crystal (PC) waveguides (WGs) and quantum dots (QDs), PC-SMZ [1,2], as shown in Fig. 1. Ultrafast switching at picosecond in speed can be operated by the PC-SMZ, based on the principle of time differential phase shift [3] due to the optical nonlinearity (ONL) of the QDs.

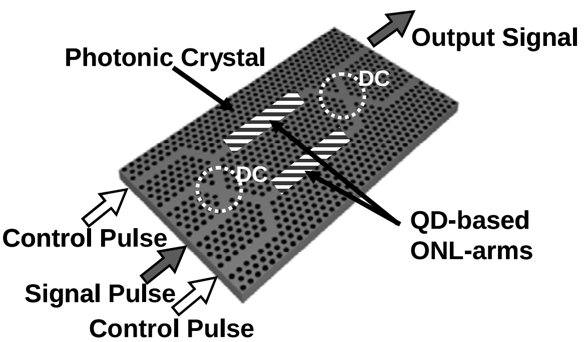

Fig. 1 All-optical switch device, PC-SMZ, composed of PC-WGs and QDs embedded in the ONL-arms. The QDs, which act as a phase-shifter of signal pulses, are preferred to be limited in the ONL-arms.

Ideally, the embedded QDs areas should be localized in the ONL-arms for reducing propagation losses of control pulses (CPs) and signal pulses (SPs) due to linear absorptions by the QDs. To realize such QDs partially embedded in PC-WGs, we have so far developed selective-area growth (SAG) technique for self-assembled InAs-QDs [4,5].

Here, we reported on an application of the SAG technique to fabricate PC-WGs with partially embedded QDs, and measurements of the ONL-induced phase shift of SPs in the PC-WG by using pump and probe method.

2. Experimental

Sample preparations

We prepared a GaAs-based straight PC-WG composed of an air-bridge-type 2DPC slab and embedded InAs-QDs in a selective-area in the WG [6]. For SAG of the QDs, we employed the metal-mask (MM) combined with molecular beam epitaxy (MBE) method [4], as schematically shown in Fig. 2.

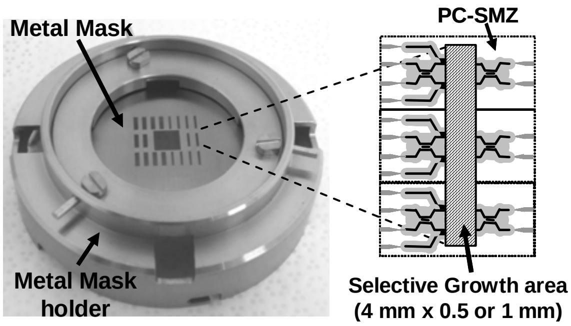

Fig. 2 Metal-mask for the SAG of QDs. Windows pattern on the mask is designed for fabricating PC-SMZ.

The MBE grown sample was then transferred to electron beam lithography and dry etching processes for fabricating the air-bridge-type 2DPC slab. At input and output ports of the PC-WG, solid immersion lens structures [7] are prepared to improve the coupling efficiency.

Pump/Probe measurements

We utilized two-color pump and probe setup for measuring amplitude and phase shift of SPs induced by CPs [1]. The SPs and CPs were collinearly coupled into the PC-WG. The ONL-induced amplitude and phase shifts of the SPs were measured by lock-in-based heterodyne detection.

3. Results and Discussion

PC/QD waveguide fabrication

Figure 3 (a) shows an optical microscope image of a fabricated sample. The area surrounded by the dashed lines is embedded with the QDs. A photoluminescence (PL) intensity mapping obtained from the same area in the

Fig. 3 (a) exhibits clear PL emission of 1.29μm in wavelength from QDs grown in a selective area, as shown in Fig. 3 (b). These images indicate successful fabrication of the PC-WG, embedding the selective area grown QDs. We have obtained PC-WG with various SAG lengths: 125 μm, 420 μm, 660 μm.

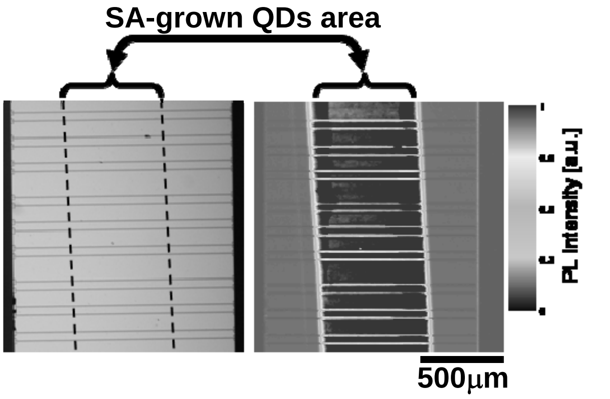

Fig. 3 (a) Optical microscope image of a sample with PC/QD WGs. (b) PL intensity mapping from the sample. High PL intensity of 1.29μm in wavelength obtained from SA-grown QDs clearly demonstrates successful SAG.

ONL-induced phase shift

Figure 4 shows typical ONL-induced phase modulation of SP against time delay between the CP and the SP. The wavelengths of the SP and the CP were set to 1310nm and 1290nm, respectively. The energies of the SP and the CP were estimated to be 33.8 fJ/pulse and 338 fJ/pulse, respectively. In this case, the phase shift was around 45 degrees.

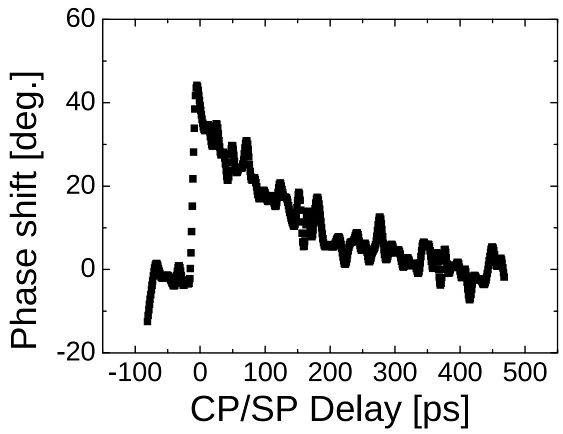

Fig. 4 ONL-induced phase shift of SP against time delay between CP and SP.

Figure 5 summarizes the excitation (CP) energy dependent phase shift as a function of the SAG length. The net excitation energy for one CP in the PC-WG is estimated from the coupling efficiency into the PC-WG. The wavelength and energy of the SP is 1320nm and 33.8 fJ/pulse, respectively. These data show that the phase shift of the SP increases with the SAG length and excitation energy.

The maximum phase shift value was approximately 55 degrees. Considering the SP phase shift should be at least 180 degrees for PC-SMZ operations, further improvement of the ONL efficiency is necessary as a next step, e.g., by QD stacking growth or utilizing the slow-light in the hetero V_g PC-WG [8].

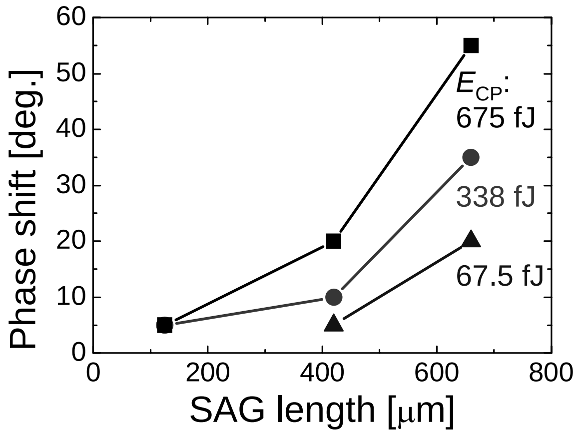

Fig. 5 Dependence of phase shift value obtained from SP on SAG length and excitation energy.

4. Conclusions

We have succeeded in fabricating a PC-WG embedding selective-area grown single QD layer and confirmed phase shifts of SPs due to the ONL of the QDs. The phase shift value depends on the length of the QD area in the PC-WG and the energy of CP. Maximum phase shift attained to 55 degrees for the sample embedded with 660-μm-lengh single QD layer at 675-fJ CP energy.

Acknowledgements

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