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Nanophotonic technologies for PC-SMZ-based all-optical flip-flop Switch: PC-FF

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1. Introduction

Nano-photonic technologies of GaAs-based two-dimensional photonic crystal (2DPC) slab waveguides and InAs-based quantum dots (QDs) are reviewed for symmetric Mach-Zehnder type [1], ultra-small and ultra-fast all-optical switch (PC-SMZ) [2,3] and optical flip-flop device (PC-FF). In the first phase of this work, ultra-fast (~ps) and ultra-low energy (~100 fJ) switching has been demonstrated using the PC-SMZ chip with 600 μm × 300 μm in size. In the second phase, the concept of the PC-FF based on the dual PC-SMZs for providing a latch function has been proposed for a future ultra-fast optical digital processor [4]. One of the priority subjects is to establish a new design method, i.e., topology optimization (TO) method of the 2DPC waveguide with wide/flat bandwidth, high transmittance and low reflectivity. Another one is to develop a selective-area-MBE growth technique with a metal-mask (MM) method for high-density and highly uniform InAs QDs with large optical nonlinearity (ONL). Recent results regarding these subjects are shown.

2. Concept of optical flip-flop device: PC-FF

The PC-SMZ is switched by two control pulses, i.e., set and reset pulses, suggesting a pseudo optical flip-flop (FF) operation. However, an "on-state" of the PC-SMZ is restricted by the carrier relaxation time in the semiconductor ONL material (this decay time is ~ 100 ps in this experiment). By using this result, unique techniques for changing into the normal FF device are proposed, as shown in Fig. 2

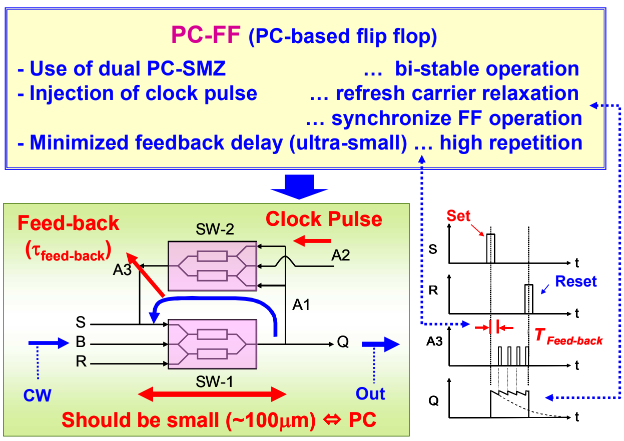

Fig. 1 Schematic diagram and time chart showing the principle of the PC-FF.

[4]. That is, an output (Q) signal of the PC-SMZ (SW-1) impinges into inputs of another PC-SMZ switch (SW-2) through a feed-back line (A1) along with another input (A2) pulse (clock pulse in this case). An output (A3) of the SW-2 is combined to the set pulse (S) for the SW-1. As shown by the time chart in the lower right-hand side, this waveguide connection leads to the successful FF (bi-stable) operation. The clock pulse (A2) serves as a refresh pulse to expand the "on-state" period against the relaxation of the carrier, while the feed-back signal (A3) restricts the clock pulse so as to be controlled by the set (S) and reset (R) pulses, thus synchronizes the FF operation. The last behavior is essential for practical application to the digital circuit in general. Feasibility of this idea has already been verified by the computer simulation, as shown in Fig. 3, where a width of set-reset pulse, feed-back time and carrier relaxation time were 32 ps, 10 ps and 100 ps, while repetition times of the S/R pulses were 400 ps (corresponding to the FF rate of 2.5 GHz) and 100 ps (10 GHz), respectively for the periodic input. The figure also shows the successful calculated result and eye pattern for the random input, too. The possibility of the 40 GHz FF rate is now under calculation by optimizing structure parameters.

It should be emphasized that, when we consider the high-rate FF operation, say, at 40 Gb/s and beyond repetition rate, the feed-back delay time (shown by $\tau_{feed-back}$) should be much smaller than the carrier life time (~100 ps here). From a simple calculation of the $\tau_{feed-back}$, this implies that the length of the device should be ~100 μm or less. This requirement can be first satisfied by an extremely miniaturized device such as 2DPC.

2. Key Issues for PC-FF Technologies

Development of the PC-FF requires several new problems for design of the 2DPCs and fabrication of the QDs. Figure 4 shows such research items categorized in the PC and QD. The most important problem of the PC is to make the band of the 2DPC wider and more flattened than ever. This is because the total waveguide configuration becomes more complicated with an increased number of bends, directional couplers and intersections, while a conventional design method has a limitation in improving this problem. Here, a new design method named topology optimization (TO) [5] is shown in response to this demand. On the other hand, the problem of the QDs is to selectively grow the QDs with a different wavelength at the different PC-SMZ

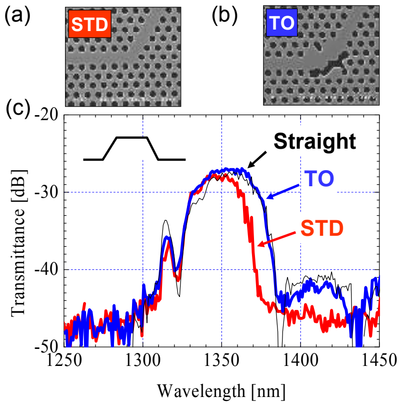

Fig. 2 The transmittance spectra of the samples with four bends for STD- and TO-design.

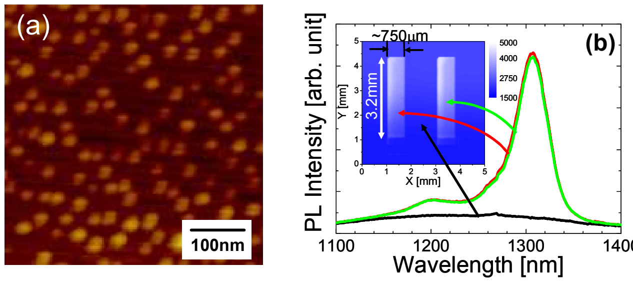

Fig. 3(a) AFM image of QDs grown on unmasked regions. (b) PL spectra from unmasked (red and green lines) and masked regions (black line). PL intensity mapping is shown in the inset.

position, as shown in Fig.2. For this purpose, a metal-mask (MM) MBE method [6] has been developed and major requirements have already been realized. In the later sections, some of the results will be shown.

3. TO method

The TO method has been developed for design of the PC structures very recently. The optimized patterning is not restricted to the uniform hole pattern but allows a deformed one. A typical example for the bend waveguide is shown in the in Fig. 2. The figure compares the standard and TO designs, as shown by the Fig. 2 (a) and (b), respectively. For the design of the bend, a hexagonal lattice (lattice constant *a*) of air holes in a dielectric substrate and a line defect waveguide composed of one missing row of air holes were considered. In Fig. 2 (c), transmission spectra for the standard (STD) and TO method are shown in red and blue, respectively. It is found that the transmission for the TO design is almost the same as that for the straight waveguide, thus largely improved in particular in the vicinity of the band gap range. As shown by this example, the effectiveness of the TO method has been verified experimentally as well as theoretically.

4. Selective growth by MM method

Another important subject for the PC-FF is to develop the selective-area growth of InAs QDs for positioning ONL materials to the designed area. The MM method enables us to grow the QD ensemble selectively in the area of several tens to several hundred μm in size. Figure 3 shows the results by the MM method, which can provide can provide InAs QDs with a surface density of $3\times10^{10}/cm^2$ in the unmasked area only and a photoluminescence (PL) characteristics with a PL peak wavelength at around 1280 nm and a FWHM (full width at half maximum) of approximately 38 meV, almost equal to those of InAs QDs grown without the MM. In addition, the QDs' emission wavelength can be controlled without any extra optical degradation by inserting a strain reducing layer (SRL) [7] on the QDs. The effectiveness of a SRL insertion on the QDs has been confirmed experimentally. The PL peak wavelength of QDs was red-shifted from 1240 nm to 1320 nm as the SRL thickness was varied by 6 nm, maintaining the FWHM of the PL peak around 30 meV. This result indicates that the SRL insertion is effective for controlling the absorption wavelength of the selective-area-grown QDs between 1285 and 1300 nm, needed for operating the PC-FF.

In this way, all of the nanotechnologies for both 2DPCs and QDs shown here are now being applied to implementation of the PC-FF. The current target of the PC-FF is a SR-FF (set/reset flip flop) for the 1st stage and a D-FF (delayed flip flop), essential for practical application to the digital circuit is being prepared for the 2nd stage in this PC/QD-based photonic integrated circuit.

5. Conclusions

Nano-photonic technologies of GaAs-based 2DPC slab waveguides and InAs-based QDs were reviewed for achieving the PC-SMZ and new PC-FF device. In order to achieve the new PC-FF device, two advanced techniques for upgrading the PC-SMZ performances have been developed. One is a new 2DPC design method, i.e., TO method, effective for designing wide/flat-band and low-reflectivity waveguides. Another one is a selective area growth of InAs QDs by using the MM method capable of real-time observation of RHEED patterns during the MBE growth. Recent experimental results on these two technologies and scheme for implementing the optical flip flop operation have been shown.

Acknowledgements

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