

Innovative Photon-Controlling Devices Based on Artificial Optical Properties of Semiconductors

- Exploration towards Digital Photonics -

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Abstract

This project is aiming at drastic improvements in optical active functions such as light emission, amplification, and detection as well as in optical nonlinearity through innovation of optical properties of semiconductors by utilizing artificial crystal structures designed and fabricated with mono-atomic order preciseness. It is also targeting evolution of optical communication technologies by establishing fundamentals of digital photonics, or more specifically, by realizing optically-controlled digital photonic devices and circuits based on the artificial optical properties of semiconductors, including optical dynamic memories, optical logic devices, digital wavelength converters, and optical 3R repeaters.

I. Introduction

Optical communication system technologies are advancing very rapidly, that include dense wavelength division multiplexing (DWDM), high speed optical time division multiplexing (OTDM), optical packet switching, microwave/photonic access link, and photonic internetworking. Although the optoelectronic technologies have been driven by materials and devices research conventionally, the bottle neck at present seems to exist in optical devices. A part of the reasons may be attributed to the fact that the conventional optical devices have been analog devices; the amplification has been possible but the regeneration (resetting signal to noise ratio) has not been possible. In addition no optical buffer memory device has been available besides the fiber delay line. Consequently, sophisticated processing of optical signals has never been possible. What is requested for the next generation is "digital photonic devices" where there is highly nonlinear all-optical response function as shown in Fig. 1, as well as "optical memory device" that is flexible like the present electronic random access memories.

More specifically, digital functions that are necessary for all-optical networking are •high speed optical buffer memory, •high speed optical logic gate, •high speed optical 3R (reshaping, retiming, regeneration) function, and •digital wavelength conversion. In order to realize them, one needs very high optical nonlinearity with low optical power. In this particular project, we are looking at carrier-associated optical nonlinearity in semiconductors which is substantial

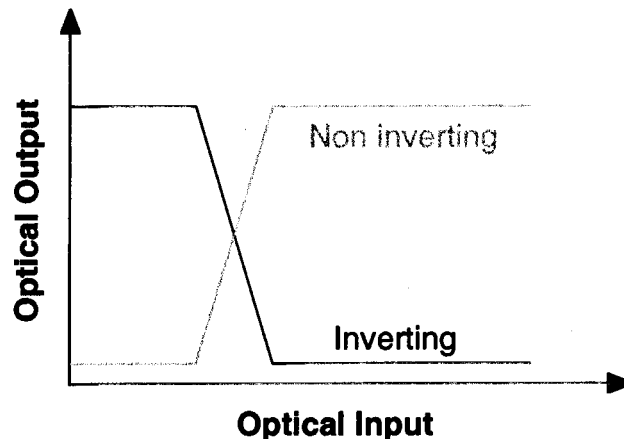


Fig. 1. Ideal transfer functions of all-optical digital devices.

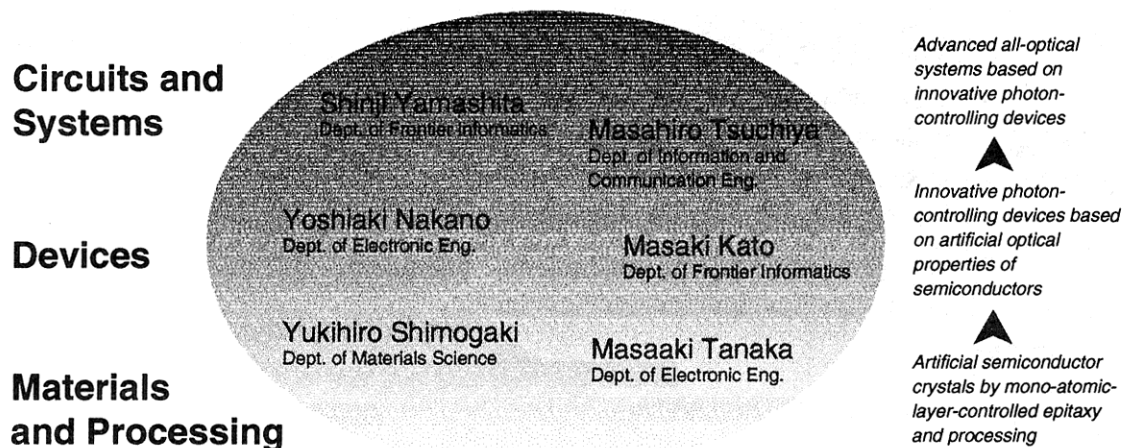


Fig. 2. Organization of the research team.

from low optical power and is fast enough if the material is properly designed.

The approach this project takes is following:

- In semiconductors, it is possible to fabricate artificial crystals which are designed and controlled to single atomic layer preciseness.
- Then, utilizing the artificial crystals, control of electron wave functions is made possible.
- As a result, alteration of macroscopic optical properties can be done by the microscopic electron wave function control.
- This should lead to large artificial optical nonlinearity necessary for digital photonic devices.

Once large optical nonlinearity is prepared, the digital photonic devices and circuits would be realized by combining it with optical resonators. This is analogous to electronic circuits where functional circuits are formed by the combination of transistors and LCR components.

The unified purpose of research in this project is, therefore, to innovate fundamental optical active functions and optical nonlinearity in semiconductors by engineering crystal structure atomic layer by atomic layer, and to realize, based on the innovated optical properties of materials, all-optical digital devices and circuits such as optical dynamic memories, optical logic devices, digital wavelength converters, and optical 3R repeaters, thus establishing fundamentals of the “digital photonics.”

2. Organization

The organization of the research team for this project is depicted in Fig. 2. The materials and processing part of the project is mainly looked after by M. Tanaka and Y. Shimogaki whereas the device part is investigated largely by Y. Nakano and M. Kato. The system part of the project is researched by M. Tsuchiya and S. Yamashita.

3. Research Plan

Figure 3 shows the planned schedule of research over the five year period of the project. In accomplishing the purpose of the project, it is imperative to have epitaxy technology with atomic order accuracy (in particular, the interface abruptness is essential), sub micron delineation and etching techniques, and simulation technology to bridge the macroscopic optical properties and electron wave functions. Another emphasis is placed on the arrow in the figure which means continuous effort to transfer the fruits of research to the next higher level. This is important for having every researcher in the project focus on the unified purpose described in the previous chapter.

4. Current Research Status

As illustrated in Fig. 3, there are a number of research subjects going concurrently. In this particular symposium, we will pick up some subjects out of all and report the results more or less in detail in the oral and the poster presentations.

	1999	2000	2001	2002
Circuits and Systems	Wavelength shaping by injection-locked DFB laser and FBG (Y)	All-optical 3R repeater circuit demonstration (N,Ts,Y)		
	Ultra short optical pulse generation by semiconductor lasers (Ts)			
	All-optical wavelength conversion by four wave mixing (Y)			
	Ultra high speed EO/MO measurement technology (Ts)	All-optical TDM MUX/DEMUX circuit demonstration (N,Ts,Y)		
Devices	DFB SOA all-optical digital wavelength converter (N)	Digital all-optical switch by sub-band transition in III-N (N,K)		
	DFB SOA all-optical flip flop (N,K)			
		Magneto-optic switch by Faraday effect (Ta,N)		
		Various all-optical devices by ATCQW electro-absorption (N,K)		
	Negative-chirp EA optical modulator by Al-based ATCQW (N,K)	Integrated optical isolator (Ta,N)		
Materials and Processing	Monolayer MOVPE of As, P, Al-related materials (S,N,K)			
	Monolayer MOVPE of group III nitrides (S,N,K)			
	Logic MOC-PIPE of group III nitrides (S,N)			
	Al-Fe-Al ferromagnetic/semiconducting hybrid multilayer structures (Ta,K)			
		Use of magnetic semiconductor heterostructures (Ta,K)		
	Computer-aided design technology of artificial crystal structures (N,K)			

Fig. 3. Schedule of research and development over the period of the project.
(N: Nakano, S: Shimogaki, Ta: Tanaka, K: Kato, Ts: Tsuchiya, Y: Yamashita)

4.1 Fabrication of InGaAsP/InP High-Mesa Waveguide MZI Optical Switches

In the fiscal year of 2000, we studied fabrication process of Mach-Zehnder interferometer (MZI) optical switches in order to apply the giant electrorefractive effect achievable in the asymmetric triple coupled quantum well (ATCQW) structure (that we proposed last year) to optical switching.

Illustrated in Fig. 4 is a schematic drawing of the MZI switch fabricated. As a preliminary experiment, bulk InGaAsP on an InP substrate with photoluminescence wavelength of 1.41 μm was used for the medium of phase modulation region. The waveguides were made into polyimide-buried high-mesa structure so as to minimize dimension of the multimode interference (MMI) couplers and to enlarge overlap between the optical mode and modulation field. The waveguides were formed by utilizing the reactive-ion-beam etching (RIE) with cyclic injection of methane/hydrogen and oxygen developed last year (Fig.5).

Optical switching characteristics measured for the TE mode at wavelength of 1.55 μm are shown in Fig. 6. The measured switching voltage, 3 V, is very low as that of bulk optical switch. From this result, the product of phase-modulation region length and switching voltage was calculated to be 1.5 V \cdot mm, which seems, to the best of our knowledge, the lowest ever reported. It also had low polarization and wavelength dependences. Consequently, the

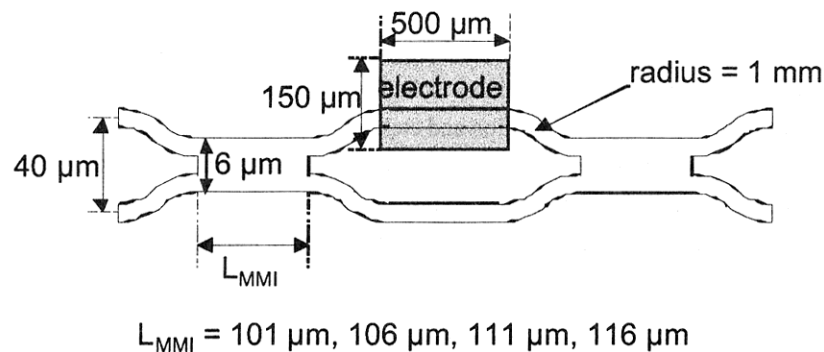


Fig. 4. Schematic of the high-mesa MZI optical switch fabricated.

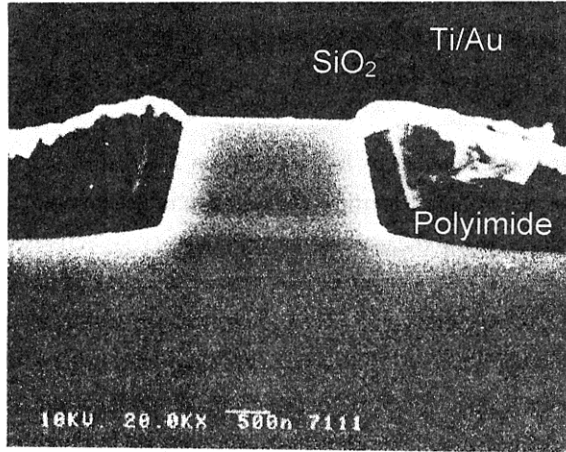


Fig. 5. Cross-sectional SEM photograph of the polyimide-buried high-mesa waveguide

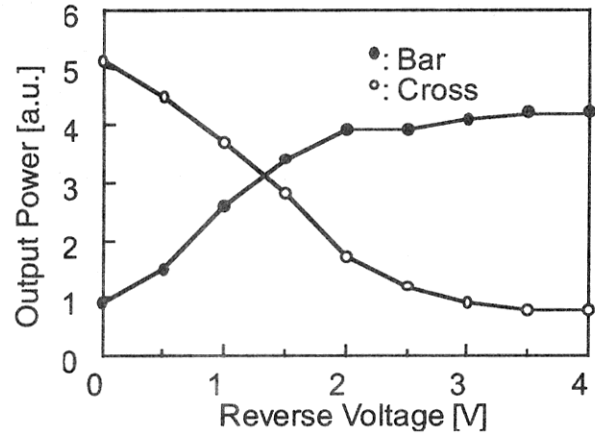


Fig. 6. Optical switching characteristics with switching voltage as low as 3 V.

structure was found to possess ideal characteristics as an optical switch. We are now trying to incorporate the ATCQW into it for obtaining ultimate performances.

On the other hand, toward all-optical processing, we have proposed MZI optical switches based on optical nonlinearities appearing in quantum well electroabsorption modulators. Its detail is described in a following chapter.

4.2 Fabrication Process of Directionally-Coupled SOA

Another all optical device studied in this project is the directionally-coupled semiconductor optical amplifier (DC SOA) whose wavelength conversion characteristics have been demonstrated in previous years. Nevertheless, its full functioning has not been available because the coupled two amplifiers shared a single electrode and therefore independent current injection into the two amplifiers was not possible. Electrode separation in the DC SOA thus needs to be accomplished. Here we established oblique electron-beam evaporation method for self-align electrode separation. A laser structure with a 0.8 % compressive strain InGaAsP MQW active layer ($E_g = 1.55 \mu\text{m}$) was grown on an n-InP substrate by MOVPE. The directional coupler pattern was made by photolithography, then selective wet etching process was followed to make parallel ridge-type waveguides (Fig. 7). Electron-beam evaporation of Al_2O_3 and liftoff were performed to make a current-blocking region. To separate the electrodes for the coupled waveguides of the DC-SOA, we used oblique electron-beam evaporation; the Au/Ti electrode was deposited at 75-degree incident angle. Because the incident angle was larger than the ridge-waveguide's mesa angle (approx. 55-degree), the mesa shaded the region between the two coupled waveguides from Au/Ti electrode evaporation (Fig. 8).

4.3 Other Activities

Other recent achievements which are not covered by this proceedings will also be presented at the symposium.

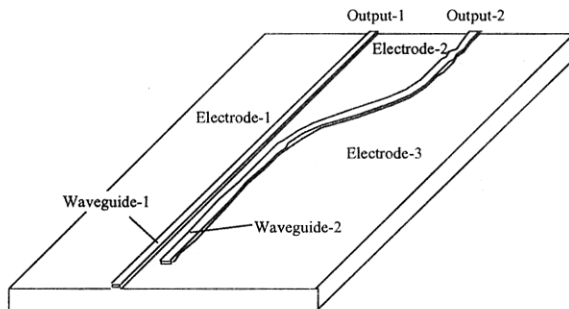


Fig. 7. Schematic view of electrode separated DC-SOA.

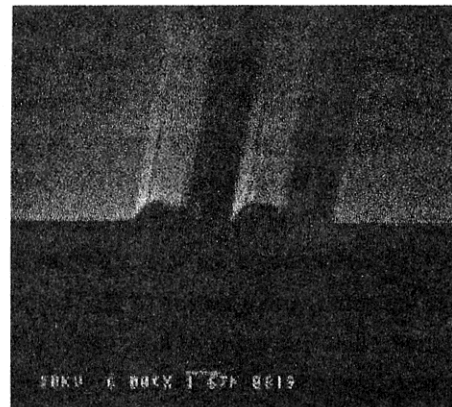


Fig. 8. A SEM photograph of the directional coupler section whose electrodes were successfully separated.