InGaAsP/InP Compact Monolithic SOA-Integrated Mach-Zehnder Interferometer All-Optical Switches by Single-Step Selective-Area MOVPE and their Switching Performance

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Abstract: Compact (3.5 x 1mm) monolithic Mach-Zehnder interferometer optical switch circuits were fabricated by single-step selective-area InGaAsP/ InP MOVPE and dry etching. Static switching performance, measured with current injection into an integrated SOA on the interferometer arm, includes 18π phase shift by 60mA. Preliminary dynamic all-optical switching experiments revealed carrier recovery time in the selective-area-grown SOA of about several hundred picoseconds.

Keywords: all-optical switch, selective area growth, monolithic integration, Mach-Zehnder interferometer

Introduction

SOA (semiconductor optical amplifier)-integrated Mach-Zehnder interferometer optical switches attracted much attention these years for there capability of processing ultra-fast optical data streams [1-4]. In particular, monolithically integrated all-optical switches are important for their compact size, stability, and low cost [2-4]. However, fabrication of such devices was not simple because they generally require bad yield etch-and-regrowth technique for active and passive components integration. On the other hand, the selective area growth (SAG) technique has also been known as another simpler technique for its requiring of only one step epitaxy, though its applicability has been limited. We previously reported fabrication and static switching measurement of shallow ridge waveguide type optical switches [3]. In this paper, we report fabrication of compact size high-mesa (deep ridge) waveguide type switches and their static switching performance with current injection as well as preliminary dynamic switching with optical control pulses.

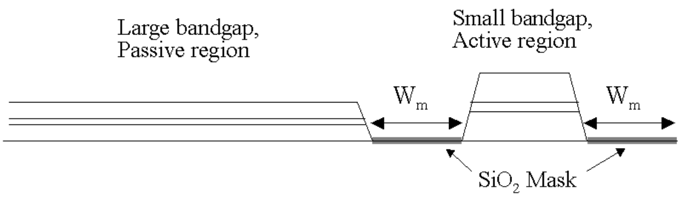


Fig.1. *Schematic view of Selective Area Growth.*

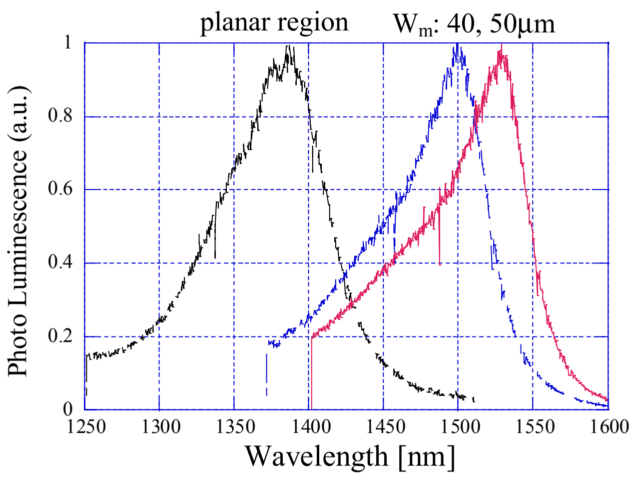


Fig.2. *Photoluminescence from planar (passive) region and SAG (active) regions (W_m=40, 50µm).*

SAG for monolithic integration

Depicted in Fig.1 is the schematic of the SAG technique. The SAG (active) region is sandwiched by SiO_2 mask film, resulting in faster grow speed than planar (passive) region due to more supply of grow source. Monolithic integration with SAG technique is enabled by large bandgap shift in SAG region. The first reason for this shift is the thicker wells of SAG region in MQW (multi-quantum well), resulting in lower quantum levels than in planar region. The second reason is the larger incorporation of

In source than Ga source, and thus shrinks the bandgap of SAG region furthermore. Fig.2 shows the PL (photoluminescence) of planar region and SAG region with SiO_2 mask width of 40µm and 50µm. The PL peak in planar region is 1380nm; in SAG region it shifts to longer wavelength, i.e. 1500nm for W_m=40µm and 1530nm for W_m=50µm. Up to 150nm PL peak shift enables the active components to be integrated in SAG region, while passive components work transparently in planar region. In the following sections, we describe fabrication and measurement of switches with 50µm width SAG region.

Design and Fabrication

To achieve compact size, we adopted high-mesa (deep-ridge) type waveguide for passive components for strong confinement of guided lightwave. With the strong confinement structure, the width of MMI (multi-mode interference) couplers can be narrow (and thus shorter MMI length) but still excites enough higher order modes for self-imaging, and bend radius can be small with little radiation loss. In our design, the width and length was each 12µm and 200µm for 3dB MMI couplers; bend radius was mostly 500µm, except for 800µm at the control input port (where larger bend radius does not effect the length of the total switch). The width of SOA and other parts of the passive waveguide was 2.5µm. The two control light input ports and central signal input port were spaced with even intervals of 250µm, for the future experiments with tapered fiber array where we could couple two control pulses together with a time delay for push-pull operation. The total length

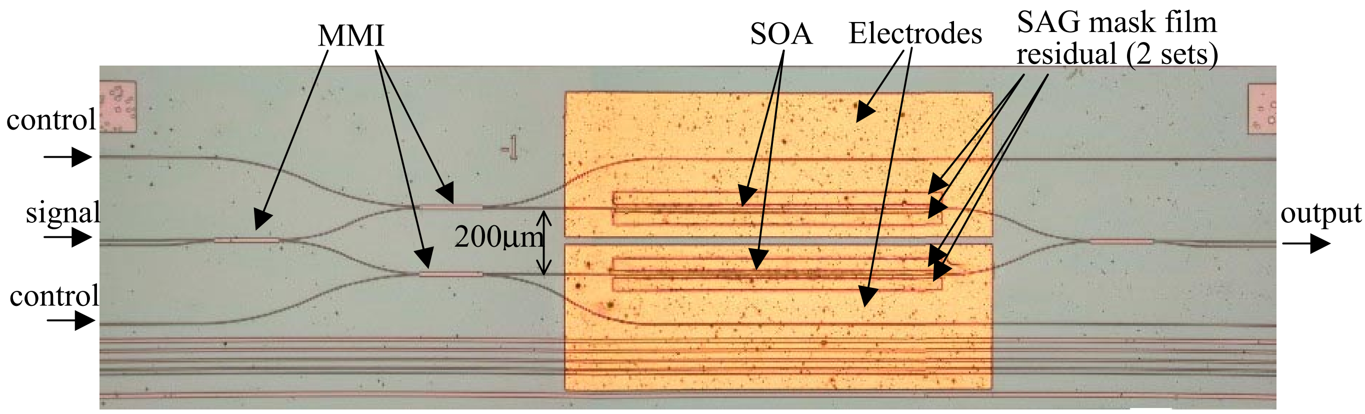
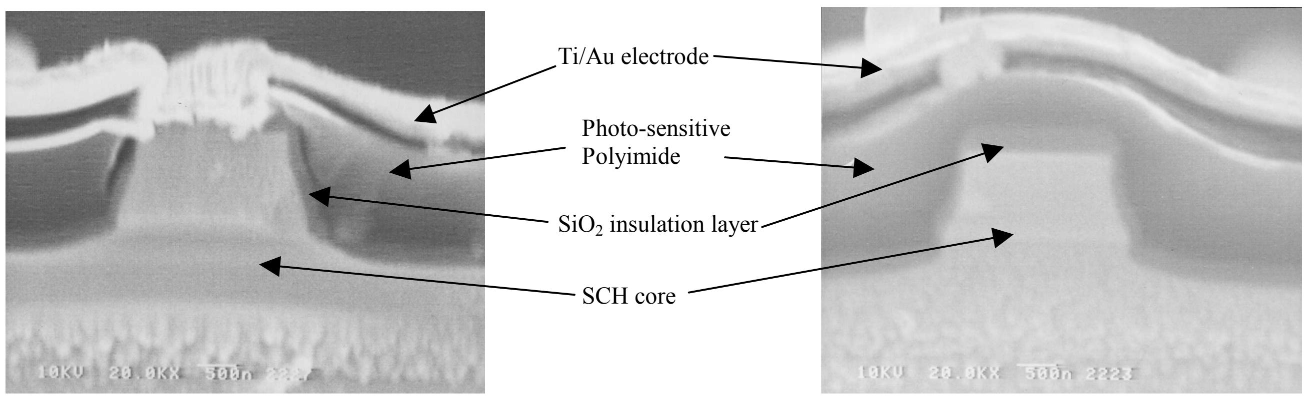


Fig.3. Microscope photograph of fabricated switch. Four MMI couplers were fabricated in planar region and two SOA's in SAG region. The spacing between two SAG regions is 200µm.



(a) SOA **(b)** Passive waveguide

***Fig.4. SEM** Section view of SOA and passive waveguide. .*

of the switch was 3.5mm. Fig. 3 is the microscope photograph of the fabricated switch.

The waveguide mesa was formed with ECR (Electron Cyclotron Resonance) ion etching machine. SiNx film was used as etching mask and the switch pattern was defined with photolithography. Though the etching depth 1.6μm was the same for both SAG region (SOA) and planar region (passive waveguide), due to different upper InP clad thickness, etching went thoroughly through the SCH (separate confinement heterostructure) core layer with passive waveguide, while stopped above the core layer with SOA mesa, as can be seen in Fig.4.

The contact opening for SOA electrode was done with photosensitive polyimide. After the waveguide mesa forming, SiO_2 insulation film was sputtered and then photosensitive polyimide was spun over the substrate. With another photolithography, only the SOA part formed opening windows. Then the electrode contact was established after SiO_2 insulation layer wet etching, Ti/Au layer EB (electron beam) evaporation.

Measurement

First, we measured the static switching performance with changing current injection to SOA's. Fig.5 shows the experimental setup, where the signal light was coupled into the input port of the optical switch through a PC (polarization controller) to select TE or TM mode. A tapered fiber was used to couple the signal light into semiconductor waveguide. Current bias to the upper SOA I_1 was fixed to 80mA, while current I_2 to the lower one was changed from 0 to 160mA. The output signal was coupled into a BPF (band pass filter) through a tapered fiber to cut off ASE (amplified spontaneous emission) from SOA, and then lead to a power meter.

Depicted in Fig. 6 is the static switching result with both output ports, TE and TM modes. The input light wavelength was 1540nm. One can see that phase shift of 14π (18π) occurred with TE mode when changing I_2 from 0 to 60mA (160mA), while only less than 7π (11π) occurred with TM mode in that range. This is due to much less gain change in TM mode with current injection, and

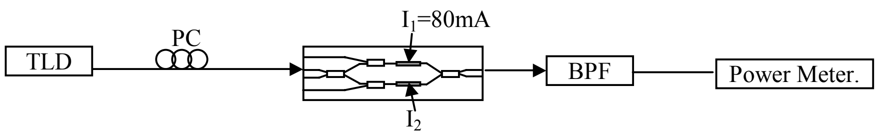


Fig.5. *Experimental setup for static switching by current injection. TLD: Tunable Laser Diode. PC: Polarization Controller. BPF: Band Pass Filter.*

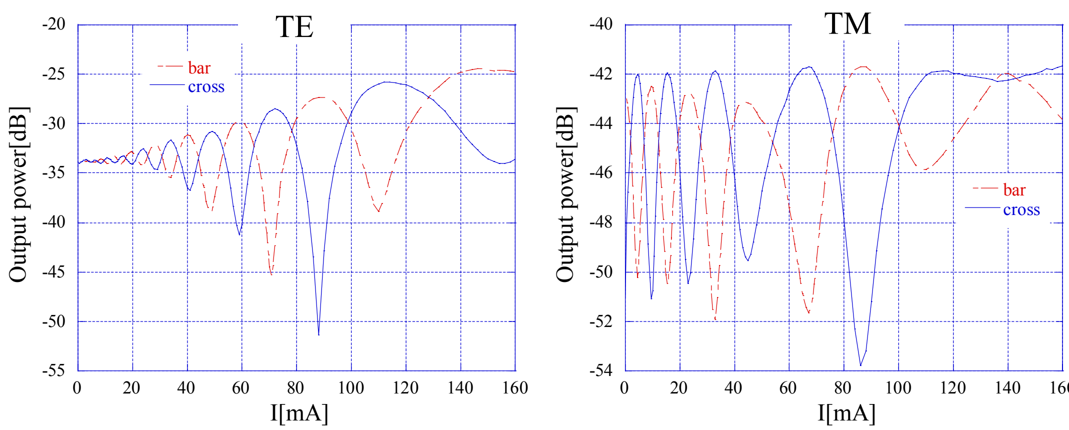


Fig.6. *Switching performance with current injection to one SOA. Input signal was 1540nm with this result. I_1 injected to upper SOA was fixed to 80mA, and I_2 to lower SOA was changed from 0 to 140mA. Phase shift of 14π occurred for TE mode when changing I_2 from 0 to 60mA, while only less than 7π phase shift occurred for TM mode in that current range.*

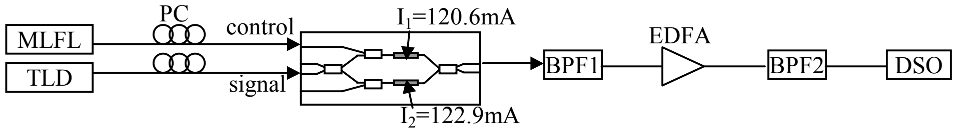


Fig.7. Experimental setup for pulse response measurenent of all-optical switch. MLFL: mode-locked fiber laser. TLD: tunable laser diode. PC: polarization controller. BPF: band pass filter. EDFA: erbium-doped fiber amplifier. DSO: digital sampling oscilloscope.

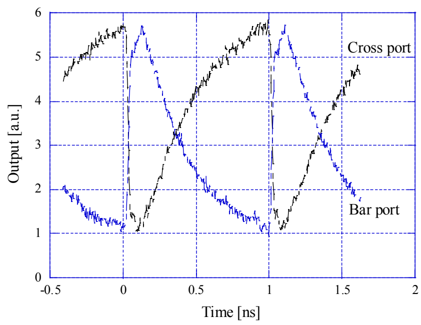


***Fig.8.** Pulse response of the switch at output ports. The control pulse energy induced phase shift of π was estimated to be 0.36pJ considering coupling loss and internal loss of the switch.*

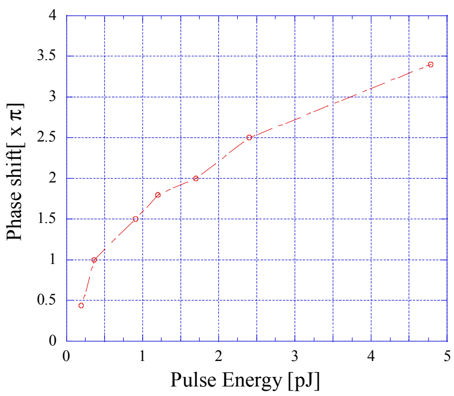


***Fig.9.** Estimated control pulse energy coupled into SOA versus induced phase shift.*

thus less refractive index change according to Kramers - Krönig relation. In TE mode, over 20dB extinction ratio was obtained when I_2 injected to the lower SOA was balanced with I_1 to the upper SOA, at around 80mA.

Preliminary dynamic switching performance was also measured with CW (continuous wave) light for signal and pulse for control light. Depicted in Fig.7 is the experimental setup. MLFL (mode-locked fiber laser) was experimentally built with a loop consists of EDFA, LN (lithium niobate) modulator, BPF and other components, and the repetition rate was 1GHz. The control pulse wavelength was 1535nm, and CW signal light was 1550nm. At the output of the switch, the control pulse was filtered off by BPF1, and only signal light was amplified by the EDFA. After cutting ASE of EDFA with BPF2, the output signal was lead into DSO (digital sampling oscilloscope), which has a photodetector sensing head. The current bias of the two SOA's was 120.6mA and 122.9mA each. Fig.8 shows the waveform of cross and bar ports measured with DSO, which indicates phase shift of π occurred in the upper SOA with control pulse energy 0.36pJ. Since the control pulse was injected into only one SOA, the relaxation time was dominated by carrier recovery time, about several hundred picoseconds. Depicted in Fig.9 is the estimated control pulse energy versus its induced phase shift in the upper SOA. Up to 3.4π phase shift was induced when the pulse energy was near 5pJ.

As a conclusion, we have successfully fabricated compact Mach-Zehnder SOA integrated all-optical switch circuits with high-mesa waveguide in the passive region. Static switching with current injection and preliminary all-optical dynamic switching performance revealed 18π and 3.4π phase shift at maximum in each case.

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References

[1] Y. Ueno et al., *Jpn. J. Appl. Phys.*, Part 2, vol. 39, pp. L806-L808, 2000.
[2] J. Leuthold et al., *J. Lightwave Technol.,* vol. 17, no. 6, pp. 1056-1066, June 1999.
[3] X. Song et al., in *Proc. ECIO'01*, Paderborn, 2001, WeA3.4, pp.102-105.
[4] T. Tekin, et al., in *Proc. ECIO'01*, Paderborn, 2001, Postdeadline Papers.