Fabrication of Silicon Photonic Devices by Utilizing Industrial CMOS Technology

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ABSTRACT

Using 0.8μm industrial CMOS technology, a 1×2 optical switch based on the carrier dispersion effect was fabricated. The device employed the conventional P-I-N structure with a typical 1μm-wide waveguide. The main process flow is presented in detail. The switching extinction ratio and the speed of the 1×2 switch are 21dB and 20ns, respectively. The fabrication repeatability is stable and reliable.

Key words: silicon photonic devices, optical switch, P-I-N, CMOS technology

1. INTRODUCTION

Silicon exhibits no linear electro-optic effect because of its centro-symmetric crystal structure, so a few researchers consider that Silicon is not a valid optoelectronic material. The carrier dispersion effect is an effect induced by the carrier injection or depletion, which can result in a change in refractive index. As previous studies show, this effect, which had been applied to photonic devices of III-V semiconductors formerly, is remarkable in Silicon. Now it is the key electro-optic effect to develop Silicon photonic devices. Silicon photonic devices based on the carrier dispersion effect have advantages in high speed, polarization-insensitive and significant change of refractive index. These devices can be fabricated by CMOS technology, so they can be easily integrated with microelectronic devices and fabricated massively and commercially at low cost.

P-I-N structure based Silicon photonic devices using the carrier dispersion effect are frequently studied. They have advantages in high efficiency of carrier injection and compact structure. Their disadvantages exist in the limited modulating speed by the carrier generation and recombination and the prominent absorption loss penalty. R. A. Soerf and his collaborators contributed much to the study of the carrier dispersion effect in Silicon[1~3], giving the empirical relation describing the change in refractive index and absorption due to the change in carrier concentration. As for the functional structures, there are MZI (Mach-Zender-Interferometer) modulators and switches, MMI (Multimode Interference) couplers, Fabry-Perot cavity, micro-ring, X junction, Y junction and Bragg reflectors[3~9]. A modulator using P-I-N

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structure with submicron waveguide had been reported [10, 11]. It had compact structure, high speed and low power.

2. A 1×2 OPTICAL SWITCH WITH P-I-N STRUCTURE

A 1×2 optical switch with P-I-N structure is considered, as Fig.1 illustrates. It consists of a 1×2 MMI coupler, a 2×2 MMI coupler and two modulation arms.

The cross section of the modulation arms is P-I-N structure, which is shown in Fig.2. The parameters in this structure satisfy single-mode condition[12]. The etched rib waveguide is 1μm in width, and the etch depth is about 0.4μm. The active region is 10μm in width. And the distance between the waveguide and active region is 2μm. The 1×2 MMI coupler is 12μm wide and 163μm long. And the 2×2 MMI coupler is 18μm wide and 425μm long. The modulation arms are 1500μm long. The necessary total length of the device is about 3200μm. With long input and output tapers for higher efficient coupling, the device is 7400μm in length.

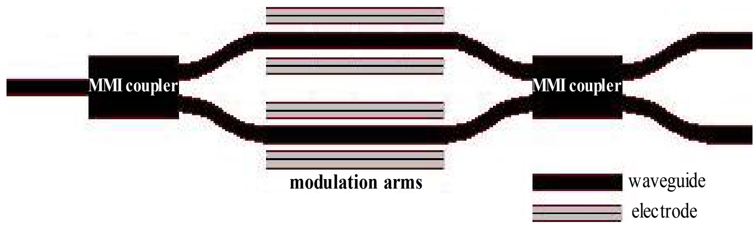


Fig.1 A 1×2 optical switch with two MMI couplers.

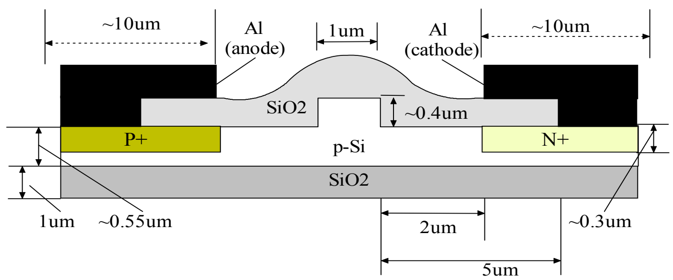


Fig.2 P-I-N structure in the modulation arms of the device.

Current is injected from the anode to the cathode. Injected current arouses the change in free carrier concentrations in the P-I-N diode; the change in free carrier concentrations results in the change in refractive index; then the phase modulation is achieved. Different modulated phase between the two modulation arms induces that the output power of the two output ports is different, so the optical switching is achieved.

3. FABRICATION FLOW AND SOME CONSIDERATIONS

Five masks, including waveguide layer, N implant layer, P implant layer, contact layer and aluminum electrode layer, should be used to fabricate the devices.

The main process flow can be summarized as Fig.3 describes. First step is to fabricate waveguide. The waveguide is etched 4000Å deep by inductively coupled plasma (ICP). Then the wafer is oxidated with a thickness of 400Å to prepare for implanting impurity. The N region is formed by implanting As+, with an energy of 120keV and an As+ dose of

$5\times10^{15}cm^{-2}$, and the P region is formed by implanting BF_2+, with an energy of 80keV and a BF_2+ dose of $2\times10^{15}cm^{-2}$. After defining N and P region respectively, another SiO2 layer with 6000Å-thick is deposited. Next is to form the contacts by etching SiO2 in certain area. Then a 6000Å-thick aluminum and silicon film is deposited, followed by chemical etching of metal to form interconnection and pads. At last, the wafer is annealed at 430 degrees centigrade for 20 minutes in N_2 and H_2 ambient to form ohmic contacts.

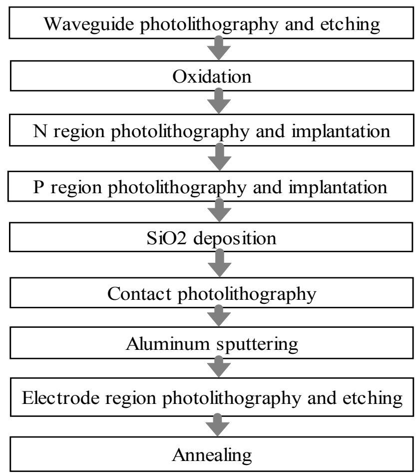


Fig.3 The main process flow used to fabricate the Silicon photonic device.

The waveguide's slenderness may result in failure in photo-resist development and disconnection of waveguide. So a protection method by adding array of rectangles to the two sides of the waveguide is considered, which is shown in Fig.4.

Check windows for etching waveguide and etching metal aluminum should be considered when layout.

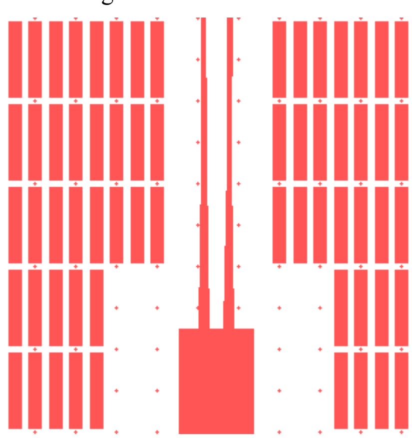


Fig.4 Layout with protection method by adding array of rectangles.

4. EXPERIMENTAL RESULTS

The device was fabricated on 6-inch silicon-on-insulator (SOI) materials. The top layer Si is 1μm thick. Fig.5 shows the photo of chips fabricated successfully by the 0.8μm CMOS technology of Hangzhou Silan Integrated Circuits CO., LTD..

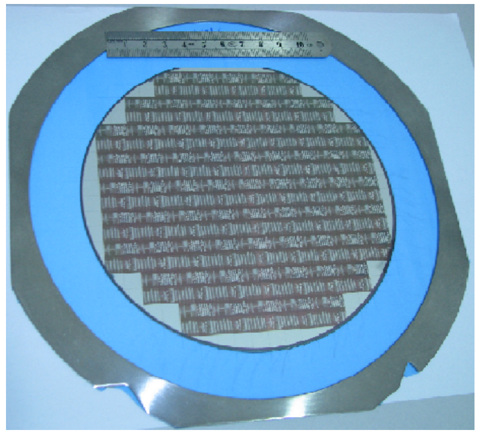


Fig.5 Chips fabricated by 0.8μm CMOS technology, more than 270 dies on one wafer.

Fig.6 shows the scanning electron micrograph (SEM) of the cross section of a waveguide. The desired width of the waveguide is 1μm, but from this figure we can see that the cross section of the waveguide is a trapezoid, whose top width is 0.767μm and bottom width is 1.085μm. This indicates that the top of the waveguide was over etched, the walls of the waveguide are not ideally upright but slightly curved. As for the others waveguides with different width, the similar fabrication results were observed.

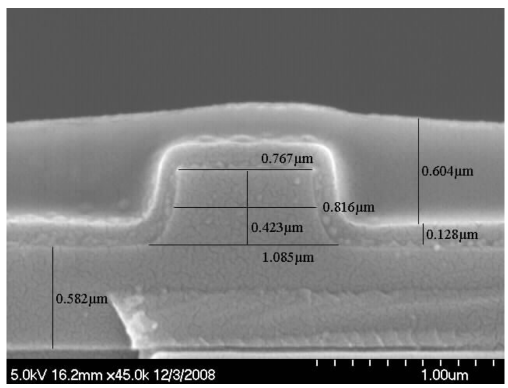
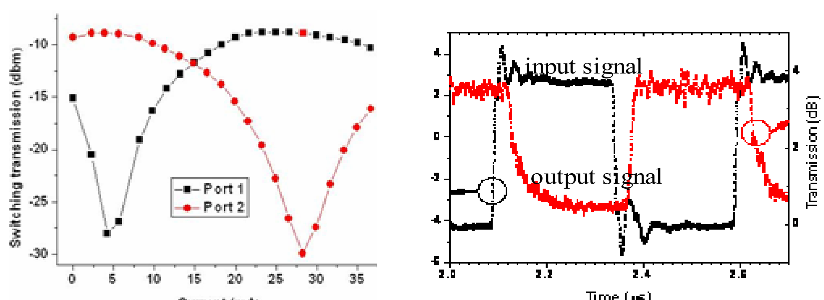


Fig.6 SEM of the cross section of a typical single-mode waveguide.



a) Switching transmission b) Response to a square wave input signal

Fig.7 The switching characteristic of the 1×2 optical switch.

The function and performance of the device were verified. The I-V characteristic measurement shows the cut-in voltage is about 0.7V, the resistance in the linear region is about 20 Ω. Fig.7 presents the switching characteristic of the 1×2 optical switch. The switching extinction ratio is 21dB when the injected current is about 21mA. The speed of the switch is about 20ns.

5. CONCLUSIONS

Other devices such as modulator based on micro-ring and 2×2 optical switch based on MMI coupler were fabricated by the same CMOS technology, too. It was our first attempt to fabricate Silicon photonic devices by utilizing industrial CMOS technology. The fabrication repeatability is stable and reliable, and the fabrication error is acceptable. Two more masks may be introduced for better results. Passivation process should be added to protect the surface of the chip, so a mask for opening electrode pads is required. Also, by considering the isolation among waveguides, another mask is required. We believe that Silicon photonic devices having more powerful functions and better performances can be designed and fabricated by CMOS technology.

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