SOI thermo-optic modulator with fast response

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Silicon-on-insulator (SOI) technology offers tremendous potential for integration of optoelectronic functions on a silicon wafer. In this letter, a 1 × 1 multimode interference (MMI) Mach-Zender interferometer (MZI) thermo-optic modulator fabricated by wet-etching method is demonstrated. The modulator has an extinction ratio of −11.0 dB, extra loss of −4.9 dB and power consumption of 420 mW. The response time is less than 30 μs.

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Recently there has been an increasing interest in silicon-on-insulator (SOI) optoelectronic devices due to the unique optical properties causing by the large refractive index difference between the core ($n_{\rm Si} = 3.5$) and the cladding ($n_{\rm SiO_2} = 1.45$). The low propagation loss of single mode SOI waveguide as −0.1 dB/cm has been achieved by wet-etching method[1], and a variety of thermo-optic and electro-optic devices have also been reported[2,3]. In this letter it proposed a SOI 1 × 1 multimode interference (MMI) Mach-Zender interferometer (MZI) modulator fabricated by wet-etching method. Because of the much higher heat conduction ability of silicon comparing with SiO_2 or polymer, the modulator obtained switching time less than 30 μs. In comparison with silica or polymer waveguide modulators[6,7], the switching times for which are 180 μs and 5 ms respectively, our device has much faster responding time. Also, due to the mature silicon processing technology, our device obtains great advantages in production cost and quality stability.

The modulator is composed of two 1 × 2 symmetric MMI couplers and two phase shift arms connected by four S-bend waveguides, as illustrated in Fig. 1. MMI couplers are selected due to their small size and good fabrication tolerance[4,5]. Light was launched into the first 1 × 2 MMI coupler, which functions as a 3-dB splitter. The two beams of equal intensity light from the splitter are separated by the S-bend waveguides to reduce the optical crosstalk and heat interference between the two arms. On the phase shift arms, there are heat films to change the refractive index in the arms. The cross section is showed in Fig. 2. If power is applied on the film to achieve an extra π phase shift in one arm, the two beams incorporated by the second MMI coupler will generate radiation mode and no light will come out from the out port.

In order to obtain high self imagine quality, the width of the MMI coupler is set to $W = 50$ μm and the length for two-fold imagine $L = 3200$ μm. S-bends with radius of 30 mm are adopted to reduce bending loss. The length of the film heaters is 1000 μm. The thermo-optic coefficient of silicon in room temperature is 1.86×10^{-4} K^{-1}, so we can change ΔnL by improving the temperature of 4.2 K.

The bond and etch-back SOI (BESOI) wafer which had buried SiO_2 layer with thickness of 1 μm and top silicon layer of 5 μm was used to fabricate the device by conventional silicon process. The rib waveguides were wet chemically etched to a depth of 1.5 μm using saturated KOH solution. The cross-section of the waveguides was trapezoidal with side angle at 54.74° because of the anisotropic etching speed along different crystal orientations. Then a 0.8-μm SiO_2 covering layer was deposited by plasma enhanced chemical vapor deposition (PECVD) on the silicon layer to protect the surface. On the phase-shift arms of the interferometer, a chrome layer of 0.2 μm and a gold layer of 0.8 μm were deposited successfully on the SiO_2 layer to form the heater film. The resistance was 9.6 Ω. Then the chip was thinned and cleaved.

Light from a distributed feedback (DFB) laser at wavelength of 1.55 μm was launched into the cleaved end face with a 9 μm diameter fiber via butt coupling. The light through the out port was collected by an object lens and then projected onto an infrared sensitive CCD. With the help of PC Laser Beam Analyzer (a PC software),

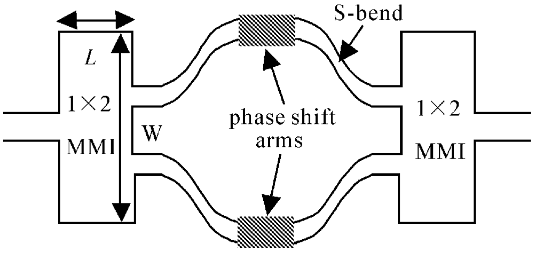

Fig. 1. Scheme of MMI MZI modulator.

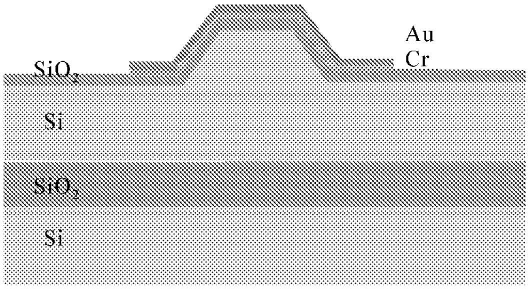

Fig. 2. Cross section of the phase shift arm.

the image could be displayed on the PC monitor. If another single mode fiber connecting to a power meter was aligned to the output waveguides in place of the lens, the outcome power was directly measured. A pair of probes was pressed on the electrodes to load driving current. To study the dynamic character of the device, alternatively, a photodiode was used for frequency response measurements, via butt coupling to a single mode fiber.

Figure 3 is a SEM photograph of SOI waveguide fabricated by wet-etching method. We can clearly see that both the bottom and side walls are rather smooth, which will result in low scattering loss. Figure 4 shows the modulation depth of the modulator against power applied to the thin film heater. The peak spacing of 420 mW corresponds to a π phase shift. The extinction ratio for the modulator is -11.0 dB (namely 92% in modulation depth) of the first valley, while -8.8 dB (87% in modulation depth) of the second valley. The extra loss of the modulator is -4.9 dB, while the extra loss is defined as $\mathrm{EL} = 10 \log (P_{\mathrm{out}}/P_0)$, where P_{out} is the output powers from the modulator and P_0 is the output power from the straight single mode waveguide on the same wafer.

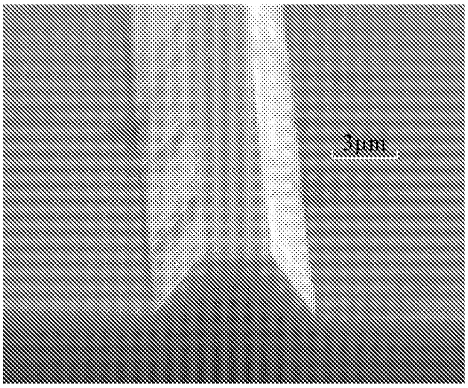

Fig. 3. SEM photograph of SOI waveguide by wet-etching method.

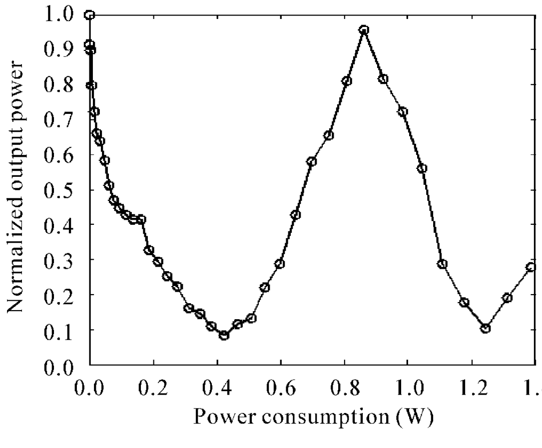

Fig. 4. Modulation depth against power applied to the film heater.

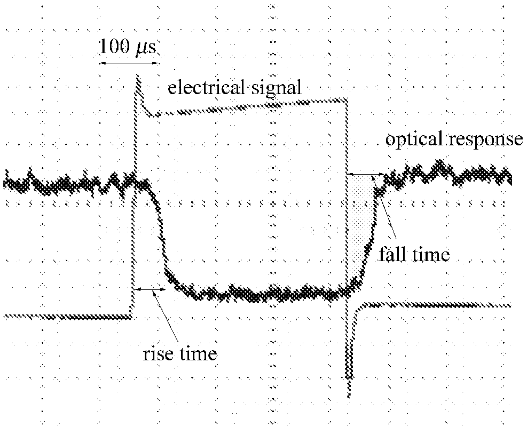

Fig. 5. Dynamic response of the modulator.

Because of high heat conductivity of silicon, SOI thermo-optic modulator has much faster responding speed. Figure 5 shows the signal of the applied power on the film heater and responding out power from the out port detected by the photodiode. Every grid represents 100 μs in time domain. We can see that the rise time is less than 20 μs and fall time is less than 30 μs.

We have fabricated a fast responding SOI thermo-optic modulator and switch by wet-etching method. The switching time is less than 30 μs, together with the static optic characters of this device: extinction ratio of -11.0 dB, extra loss of -4.9 dB and power consumption of 420 mW. This work demonstrates the potential of SOI technology for silicon based optoelectronic devices.

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