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RESEARCH ARTICLE

Improved extinction ratio of Mach-Zehnder based optical modulators on CMOS platform

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Abstract Silicon based optical modulators with improved extinction ratio (ER) of 25 dB were demonstrated on complementary metal oxide semiconductor (CMOS) platform. It was proposed that the effect of optical absorption due to free carriers accumulated in silicon should be considered in the analysis of device configuration. Experimental results presented in this study were identical with the proposed analyses. The modulators were operated with the data transmission rate of 3.2 Gbps.

Keywords silicon photonics, optical modulator, extinction ratio (ER), integration

1 Introduction

Optical components integrated in silicon-on-insulator (SOI) have many potential applications, such as system-on-chip, network-on-chip and lab-on-chip. However, all these integrated optic circuits need co-operated with micro-electronics [1,2]. Up to now, most achievements on silicon photonics have not focused on the effect of integrated components in silicon compatibly fabricated with complementary metal oxide semiconductor (CMOS) processes. In fact, many considerations have to be taken into design and development of the compatible fabrication of these integrated silicon photonics, especially for the improved extinction ratio (ER) of optical modulators.

In this study, we proposed the integrated optical modulators in SOI by the compatible CMOS processes under the modern CMOS foundry in China. And the measured results were shown, which are the high ER of 25 dB for the optical modulators, and the fast response modulator with the data transmission rate of 3.2 Gbps [3].

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2 Design

Mach-Zehnder (MZ) optical modulator in SOI shown in Fig. 1 was demonstrated using the 1×2 multimode interference (MMI) splitter and the 2×1 MMI combiner to enable broadband spectral operation with high ER as well as large fabrication tolerance. Two nanophotonic rib waveguides embedded with p-i-n diodes to form two phase shifters were shown in Fig. 1. The two phase shifters were the same with each other to ensure the balance of the carrier induced optical loss between them and therefore obtain high ER. The asymmetrical Mach-Zehnder interferometer (MZI) arms were introduced to simplify the optical characterization, with 19.2 nm free spacing range (FSR) by adding a 30 μm arm length difference. In order to enable the wafer scale online testing, gratings were utilized as the optical interconnects between the sub-micron waveguides and optical fibers. The highest coupling efficiency of 50% at 1550 nm for transverse electric (TE) modes and 3 dB bandwidth of 80 nm [4] were theoretically predicted at the etching depth near to that of the modulator waveguide.

When a forward-bias voltage is applied on the p-i-n diode, a large amount of majority carriers are forced to inject into the intrinsic region and bring the large effective index change of the fundamental TE mode in a rib waveguide. Therefore, the overlay between injection carrier and optical mode is the key factor on the modulation efficiency and the carrier induced optical absorption loss. Less carrier-induced absorption loss makes it easier to obtain large ER in MZI configuration [5], as shown in Fig. 2. The ER decreases from about 30 dB for undoped waveguides to less than 20 dB for boron doped silicon. Fortunately, the ER can be improved by a perfect design with special consideration, and high ERs are possible by tuning the driving levels and the operational wavelengths. This can be approved by the testing results. Surely, the insertion loss is really a problem for the modulators due to optical absorption at the

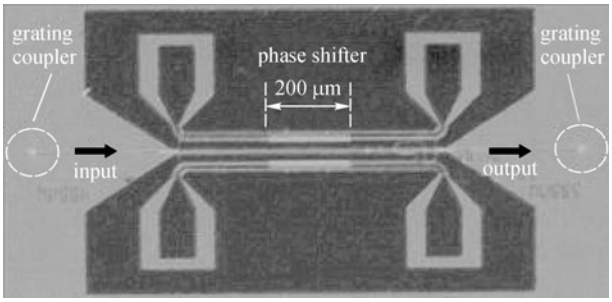

Fig. 1 Microscope image of MZ modulator fabricated in CMOS foundry

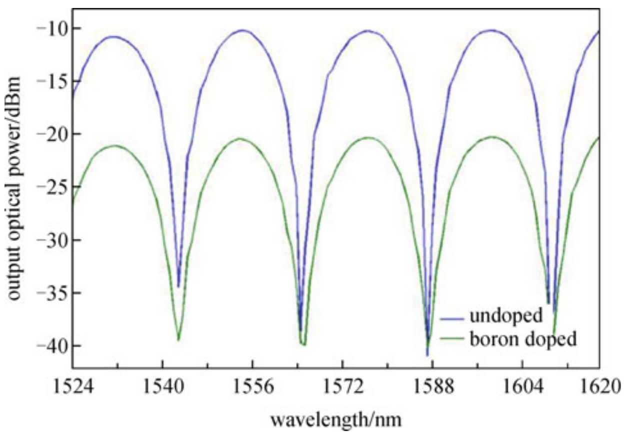

Fig. 2 Optical spectra for undoped and boron doped asymmetric MZs in silicon

modulated arms of MZ, which is an important factor in the device design and needs to be considered as the operating mode of the modulators with different optical wavelengths. The influence of the etching depth (waveguide width is 500 nm) on the modulation efficiency is also an effective factor to the propagation loss and the ER. In this design, 240 nm etching depth corresponding to 100 nm slab layer is chosen to obtain high modulation efficiency (0.35 V·mm) and low loss (2.9 dB/cm).

3 Fabrication

The designed layout is send to the CMOS foundry with the standard micro-electronic processes. Some special trials were needed for the adoption of the process flow. Figure 3 shows the scanning electron microscope (SEM) images of the fabricated optical rib waveguides and devices in SOI. The MZI modulator integrated with grating coupler was fabricated on SOI substrate with 340 nm-thick top silicon layer and a 2 μm-thick buried oxide layer, which offered high optical confinement capacity to form sub-micron cross-section of nanophotonic rib waveguide and highly efficient out-of-plane grating coupler. The fabricated grating couplers, ground-signal-ground (GSG) electrodes on both arms of modulator as well as the asymmetric MZI scheme were shown in Figs. 1 and 3. The passive components (splitters and combiners, etc.) were patterned by ultraviolet (UV) lithography before the following inducted coupled plasma (ICP) etching. At first, the optical waveguides including MMIs were defined by using UV lithography and etched about 240 nm (measured by step profiler). Then, the grating couplers were defined at the end of the waveguides by aligned lithography exposure and etched about 200 nm. The SEM images of the optical components of MZI modulator, such as (a) rib optical waveguide and (b) grating coupler, were shown in Fig. 3.

4 Results

The testing has been done to these fabricated devices. Figures 4 and 5 respectively show the optical spectra

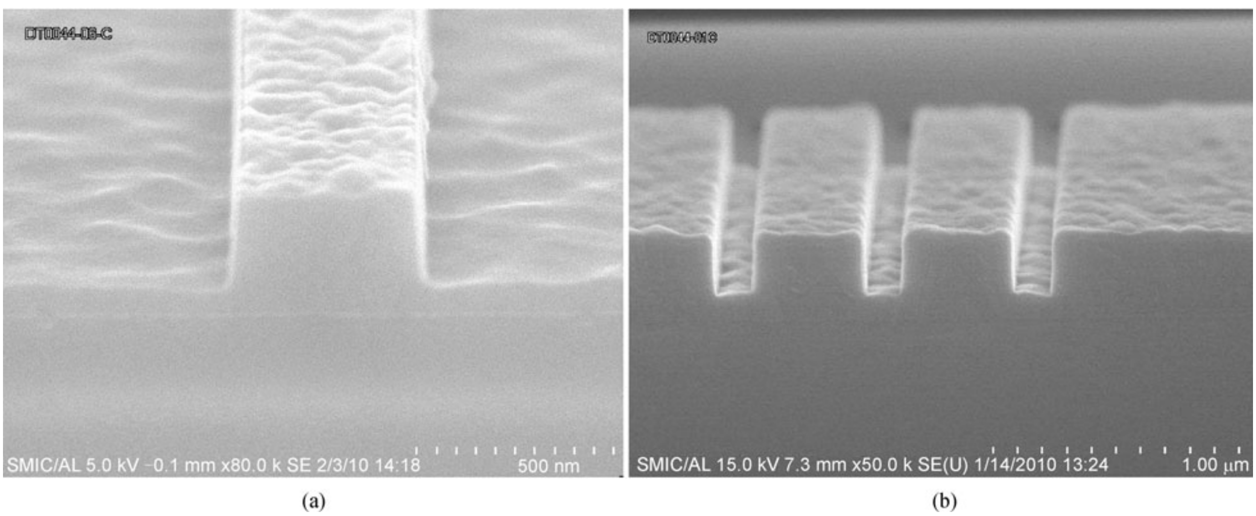

Fig. 3 SEM images. (a) Rib optical waveguide; (b) grating coupler for light in and out vertically

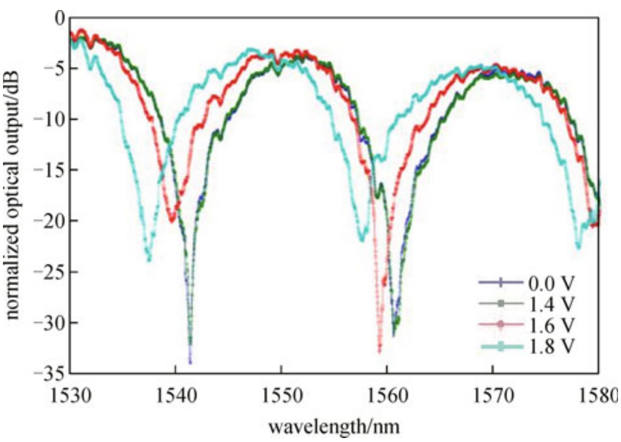

Fig. 4 Optical spectra of asymmetric MZ modulator biased at the forward voltages from 0 to 1.8 V

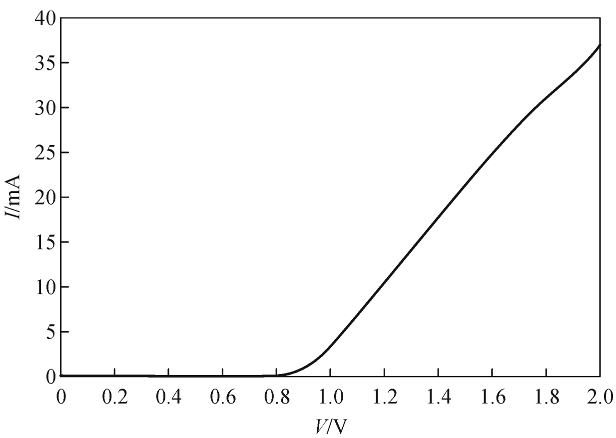

Fig. 5 *I-V* curve of PN diode for integrated active components

shifting to the bias reverse voltages and the current-voltage (*I-V*) curves of the PN diode in the active component for optical modulation. Fiber-to-fiber measurement was set up to characterize the spectral transmission of MZI modulators integrated with grating couplers. Two cleaved single mode fibers, respectively connecting to the lasers and optical spectrum analyzer, were positioned above the input and output grating at about 10° with respect to the vertical axis of the die. The optical transmission spectrum of the device was given in Fig. 4. The measured 3 dB coupling bandwidth was more than 50 nm (1530–1580 nm) with the peak wavelength of 1550 nm, which agreed with the simulation [4]. High uniform ERs of more than 25 dB were achieved in the entire testing wavelength arrange, contributing from the low optical loss [5] in the two arms of the asymmetric MZI employing MMI optical waveguides. The measured FSR was 19.2 nm, which corresponded with the simulation result very well, and indicated little waveguide cross-section variety in the fabrication. The total insertion loss of the device at around 1550 nm was normalized as 13.7 dB by deducing the excess loss of the measurement setup. The loss mainly comes from splitter/combiner (about 2 dB) and coupling loss (about 11 dB) for a pair of couplers of a testing device.

For the 200 μm long phase shifter, the *I-V* curve of the device was measured. Figure 5 shows that very low differential resistance (about 20 Ω) was obtained indicating good ohmic contact in the silicon and aluminum interface. The normalized optical output power at wavelength of 1550 nm as a function of applied direct current (DC) voltage was shown in Fig. 5. The optical power reached the lowest point at a very low bias of 1.8 V corresponding to $V_\pi L$ figure of merit of 0.36 V·mm, which was close to the simulation value (0.35 V·mm), due to the low contact resistance with perfect fabrication.

In order to speed up carriers injection and extraction, a pre-emphasis electrical signal was used to drive the forward biased modulator embedded with p-i-n diodes. This pre-emphasis signal was formed by combining two channels of non-return to zero (NRZ) signal with time delay and voltage amplitude difference between them, and then applied on the electrodes of MZI modulator by a GSG probe. The electro-optic modulation was measured by a high speed oscilloscope equipped with a high bandwidth optical detector. The NRZ signal with the peak-to-peak driving level of 2 V makes 3.2 Gbps modulation by the integrated component, as shown in Fig. 6. Further improvement of modulation speed can be achieved by optimization the doping profile and adding a matching terminator at the end of the electrodes.

5 Conclusions

In this study, the recent work on the integrated silicon photonics using the compatible CMOS processes in China was reported. The measurements of the fabricated samples

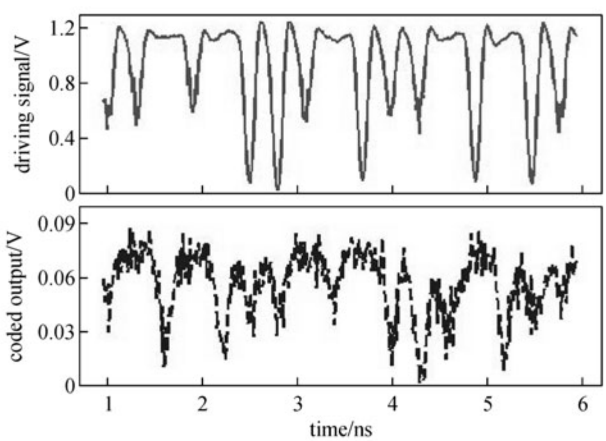

Fig. 6 Measured modulator response at the transmission rate of 3.2 Gbps

indicate that the CMOS foundries require some special consideration on our photonic design and development. The first test results show that the high ER of more than 25 dB is possible and the data transmission rate of 3.2 Gbps is available by the integrated silicon optical modulator.

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