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Operation power reduction of Si electro-optics switch by decreasing current leakage

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1. Introduction

Optical matrix switches are key components for future energy-saving networks, because they can omit optic-electric conversion. Silicon (Si) waveguide 2 × 2 Mach-Zehnder (MZ) optical switches have been developed as elements of these optical matrix switches [1,2]. In addition, electro-optic switches have the advantage of low switching power and fast switching speed [3,4,5]. Some groups have reported that the carrier lifetime plays an important role in the performance of Si electro-optic devices [6,7,8]. According to them, it is important to increase the carrier lifetime in order to improve the carrier injection efficiency. The carrier injection efficiency can be estimated by measuring the variable optical attenuator (VOA) efficiency [6]. The VOA is operated by using free carrier absorption, which is proportional to the density of the accumulated carriers. Thus, the VOA efficiency is the useful indicator of the carrier injection efficiency.

In this work, we try to increase the carrier lifetime by introducing SiO_2 passivation layer. We confirm the carrier accumulation improvement effect of the SiO_2 passivation layer by measuring the VOA efficiency and leakage current. Finally, we show the characteristics of the Si rib waveguide MZ switch with the SiO_2 passivation layer.

2. Device fabrication

We fabricated 2 × 2 MZ switches and VOAs with a Si rib waveguide p-i-n structure shown in Fig. 1. The waveguide consists of a Si core with 480-nm-wide × 200-nm-thick and Si slab of 50-nm-thick. To increase the carrier lifetime, it is necessary to reduce surface levels, which act as carrier traps. It is reported that waveguide surface passivation by silicon nitride layer is effective to increase carrier lifetime [7]. In this work, we introduced chemical vapor deposited SiO_2 passivation layer on the waveguide after waveguide etching. In the following sections, we evaluate the validity of the SiO_2 passivation layer from the fabricated devices' characteristics.

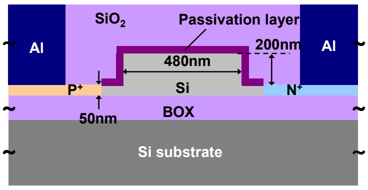

Fig. 1. Cross-sectional view of fabricated Si rib waveguide p-i-n structure.

3. Method for carrier lifetime evaluation

The forward current of p-i-n diodes can be approximated by the sum of the diffusion current and the recombination current. It is known that the recombination current (I_{rec}) is the leakage current through carrier traps and dominates at low voltage. I_{rec} and the carrier lifetime (τ) are described below [9]

$$I_{rec} = \frac{kT}{E} \sigma v_{th} N_t n_i \exp\left(\frac{qV}{2kT}\right) \qquad (1)$$

$$\tau = \frac{1}{\sigma v_{th} N_t} \qquad (2)$$

where N_t is the trap density, n_i is the intrinsic carrier density, σ is the capture cross section, v_{th} is the average thermal velocity, E is the electric field at the junction, k is the Boltzmann constant, T is the temperature, and V is forward bias voltage. We can see that decreasing N_t is necessary for increasing τ, from Eq. (2). We can also see that I_{rec} becomes lower by decreasing N_t, from Eq. (1). Thus, there is a close relationship between τ and I_{rec}. By measuring the current at a low voltage level, we can evaluate τ, i.e., the carrier injection efficiency, qualitatively.

4. Measurement results

Figure 2 shows the relationship between the attenuation at an injection current of 50 mA and the current at a forward bias voltage of 0.7 V. The VOA length is 250 μm. Both the attenuation and the current values are divided by the VOA length. We compare the VOA properties with and without the passivation layer. The VOA with the passivation layer shows low leakage current and high VOA efficiency. It means that carrier lifetime increases and carrier injection efficiency improves, respectively. We think this improvement comes from a reduction of surface levels.

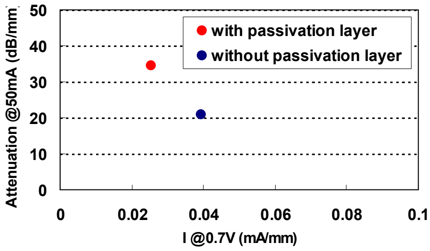

Fig. 2. Relationship between attenuation at 50 mA and current at 0.7 V.

We also measured Si rib waveguide 2 × 2 MZ switches with the passivation layer. A plan view of the switches is shown in Fig. 3. The length of the phase shifters is 250 µm. Two phase shifters are combined using 50% multi-mode interference (MMI) couplers. The input and output ports form tapered waveguides to ensure fiber coupling. Figure 4 shows the results of the relative transmittance power at two output ports as a function of driving electric power. In this measurement, the input wavelength is fixed at 1550 nm. Transmitted light power at both output ports were measured while changing the forward bias voltage applied to Arm2. The constant bias voltage is applied to Arm1 in order to compensate for the optical path length difference between Arm1 and Arm2 due to fabrication errors. The input light enters the input port a_1. At a driving electric power of 1.34 mW, the optical power switches from the output port b_2 to the output port b_1 (from the “cross” state to the “bar” state). Figure 5 shows the relationship between the switching power and the phase shifter length for other Si optical switches. To the best of our knowledge, the switching power of our switch is the lowest among switches with short phase shifters. Previously we proposed a MZ optical switch with a silicon germanium (SiGe) waveguide core to obtain efficient carrier confinement by heterostructure and demonstrated a low switching power of 1.53 mW [5]. However, the SiGe optical switch was not introduced the passivation layer. We believe that the switching power of the SiGe optical switch can be reduced further by introducing the passivation layer .

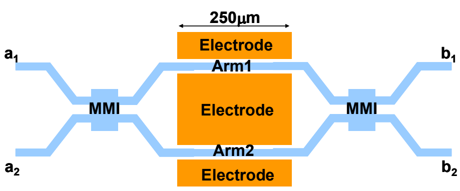

Fig. 3. Plan view of fabricated 2 × 2 MZ electro-optic Si switch.

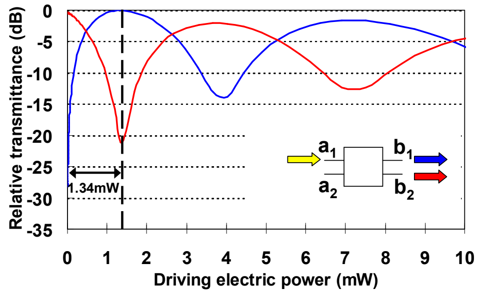

Fig. 4. Relative transmittance power as a function of driving electric power.

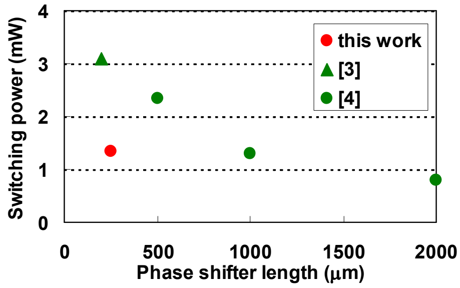

Fig. 5. Relationship between switching power and phase shifter length for various Si-based optical switches.

5. Conclusions

In this work, we have improved the carrier injection efficiency by introducing the SiO_2 passivation layer. We have confirmed the carrier accumulation improvement effect of the passivation layer by measuring the leakage current of the fabricated VOAs. We have fabricated the MZ switch with the passivation layer and demonstrated a low power operation of 1.34 mW. The switching power of the switch is the lowest among switches with short phase shifters. We believe that by introducing the passivation layer, the switching power of the SiGe optical switch can be reduced further.

Acknowledgments

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