Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp198-199

Compact and Polarization-Independent Variable Optical Attenuator Based on a Silicon Photonic Wire Waveguide with Carrier Injection Structure

Hidetaka Nishi, Tai Tsuchizawa, Koji Yamada, Toshifumi Watanabe, Hiroyuki Shinojima, and Sei-ichi Itabashi

NTT Microsystem Integration Labs., NTT corp., 3-1 Morinosato Wakamiya, Atsugi-shi Kanagawa, 243-0198, Japan
Phone: +81-46-240-2099, E-mail: hnishi@aecl.ntt.co.jp

1. Introduction

Silicon (Si) photonics is a promising technology for realizing electrically controlled optical devices [1-4]. A basic application of Si photonics is a Si variable optical attenuator (VOA) [5,6]. A Si-VOA based on a Si wire waveguide (WG) with a sub micrometer core and *p-i-n* structure shows a response as fast as a few nanoseconds and uniform attenuation in a wide wavelength range [6]. Such high-speed VOAs and their arrays would be very important devices in future telecommunications system. However, the VOA must be polarization independent. So far, Si-VOAs based on WGs with sub micrometer cores have only been operated in the TE mode, and they show an apparent polarization dependent loss (PDL). In this study, we demonstrated a low-PDL Si-VOA based on a rib-type Si wire WG with *p-i-n* carrier injection structure.

2. Design

A cross section of the Si-VOA is schematically shown in Fig. 1. The slab regions on either side of the core are ion-implanted to make a p+ region on one side and an n+ region on the other side. As a result, the device has a lateral *p-i-n* structure. When forward bias is applied, carriers are injected into the *i* region, which is the core of the WG, and the propagating light is absorbed by injected free carriers. The attenuation within the VOA can be controlled by injected current.

Here, we show a procedure for evaluating the PDL. The PDL can be expressed as the difference in attenuation between TE and TM modes : $|Att._{TE} - Att._{TM}|$. The $Att._{TE}$ and $Att._{TM}$ are calculated as $Att. = 4\pi k/\lambda$, where k is the imaginary part of the complex effective refractive-index ($N_{eff} = n + i\,k$) of the WG and λ is the wavelength. The effective indices of the TE and TM modes were calculated with a numerical mode solver. For the calculation of k, we need to determine the absorption coefficient (α) in the Si core. The α is expressed by the Drude model [7], and related to the carrier density. From device simulation, the distribution of carrier density can be assumed to be uniform in the core. We therefore determined α to be constant.

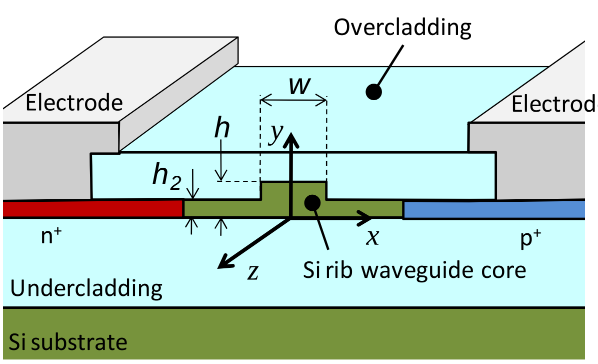

Fig. 1 Schematic of a cross section of a Si-VOA.

We changed the value of k_{TE} and k_{TM} by varying the parameters of the cross-section of the WG (See Fig. 1), which are rib height (h), rib width (w), and slab height (h_2), and determined the core shape that would provide low PDL. We found that a PDL lower than 1 dB could be obtained when the parameters were w 360 - 500 nm, h 300 nm, and h_2 40 - 80 nm (Fig. 2).

3.Fabrication process

Figure 3 shows an optical microscope image of a fabricated device. It consists of a VOA, spot-size converters (SSCs) [8] at the input and output ports, and the rib WG section. We used the silicon-on-insulator (SOI) substrate as a starting substrate, with a 300-nm-thick top Si layer and 3-μm-thick buried oxide layer. First, the rib waveguide core was fabricated by electron-beam (EB) lithography and electron-cycron resonance (ECR) plasma etching to a depth of 220 nm. Rib width was set at 3 types of 300, 360, or 440

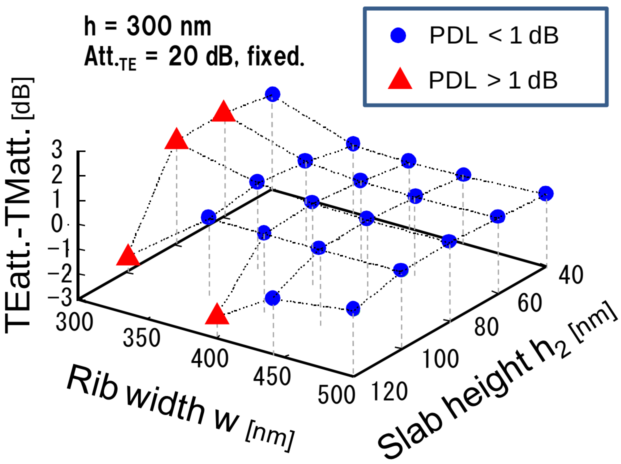

Fig. 2 $Att._{TE}$-$Att._{TM}$ calculated using w and h_2 as parameters.

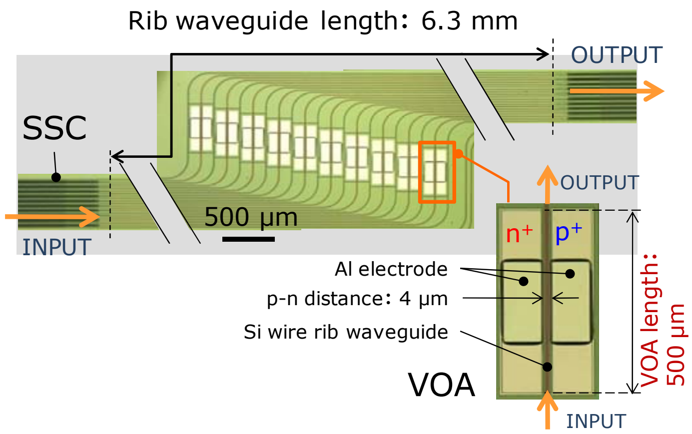

Fig. 3 Optical microscope image of a fabricated VOA.

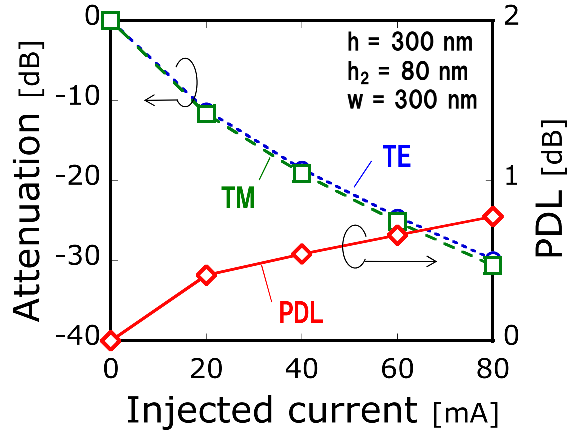

Fig. 4 Attenuation and PDL characteristics of a fabricated VOA.

nm. The lengths of the WG and the VOA were 6.3 mm and 500 µm, respectively. The p+ and n+ regions were defined by photolithography and ion implantation. The two ion-implanted regions were separated by a distance of 4 µm. Then, the slab portion around the Si taper region at the SSCs was removed by ECR plasma etching to a depth of 80 nm. Next, Al was deposited by sputtering and the Al pad was formed by wet etching. After that, we formed the second core of the SSCs and deposited an SiO_2 overcladding by plasma-enhanced CVD. Finally, contact holes above the Al pads were formed by plasma etching.

4. Results

We measured the optical transmission characteristics of the fabricated devices using an amplified spontaneous emission (ASE) light source at λ = 1530 -1570 nm. For the measurements, high-NA single-mode fibers were butt-to-butt coupled to the SSCs.

First, we evaluated the PDL from the propagation losses in the TE and TM modes, and the PDL of 0.1 dB was obtained. Next, we measured the PDL of the VOA as a function of injected current. Figure 4 shows the normalized attenuation and PDL of the VOA with the 300-nm-wide core. The attenuation values at 0 mA were normalized to be 0 dB so that we could evaluate PDL only due to the free carrier absorption in the VOA. As the injected current increased, attenuation of both modes decreased with a small difference between them. The PDL of the VOA operation was 0.6 dB at 20-dB attenuation. Moreover, we also measured the VOA with the 360-nm-wide core, and obtained the PDL of 0.8 dB at 20-dB attenuation. The fabricated VOAs showed low PDL in a wide range of core width.

5. Summary

We have designed and fabricated compact and polarization-independent Si-VOAs. The VOA exhibited excellent characteristics with the low PDL of 0.6 dB at 20-dB attenuation.

Acknowledgements

We thank Dr. Mitsutoshi Takahashi for his help with the calculation of carrier density and for helpful discussions.

References

[1] R. Soref, *IEEE J. Select. Topics Quant. Electron.*, **12** (2006) 1678.
[2] T. Watanabe, K. Yamada, T. Tsuchizawa, H. Fukuda, H. Shinojima, and S. Itabashi, *Proc. SPIE*, **6775** (2007) 67750K-1.
[3] W. Green, M. Rooks, L. Sekaric and Y. Vlasov, *Opt. Express*, 15 (2007) 17106.
[4] A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky and M. Paniccia, Opt. Express, 15 (2007) 660.
[5] I. Day, I. Evans, A. Knights, F. Hopper, S. Roberts, J. Johnston, S. Day, J. Luff, H. Tsang, and M. Asghari, *Proc. OFC 2003, TuM5* , (2003) 249.
[6] K. Yamada, T. Tsuchizawa, T. Watanabe, H. Fukuda, H. Shinojima, and S. Itabashi, *Proc. IEEE Intern. Conf. Group IV Photonics, Tokyo*, (2007) 116.
[7] R. A. Soref and B. R. Bennett, *IEEE Journal of Quantum Elecronics*, **QE-23** (1987) 123.
[8] T. Tsuchizawa, K. Yamada, T. Watanabe, H. Fukuda, H. Nishi, H. Shinojima and S. Itabashi, *Proc. IEEE Intern. Conf. Group IV Photonics, Sorrento*, (2008) 200.