A-1-1(Invited)

Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp516-517

Silicon/Ge/Silica Monolithic Photonic Integration for Telecommunications Applications

Koji Yamada[1,2], Tai Tsuchizawa[1,2], Hidetaka Nishi[1,2], Rai Kou[1,2], Tatsurou Hiraki[1,2], Hiroshi Fukuda[1,2],
Yasuhiko Ishikawa[3], Kazumi Wada[3]

[1] Microsystem Integration Laboratories, NTT Corporation, 3-1, Morinosato-Wakamiya, Atsugi 243-0198, Japan
[2] Nanophotonics Center, NTT Corporation, 3-1, Morinosato-Wakamiya, Atsugi 243-0198, Japan
[3] Department of Materials Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

1. Introduction

The explosive increase of telecommunications traffic requires large-scale integrations of photonic devices, which can provide high-functionality, low-power, and low-cost telecommunications modules. Silicon (Si) photonics is a breakthrough technology that would satisfy these requirements. However, the hurdles to the telecommunications applications are still very high for Si photonics because the standards for telecommunications are very severe. In particular, insertion losses and polarization dependence have been serious obstacles to practical applications. To overcome these obstacles, we have developed a photonic platform in which Si, germanium(Ge) and silica photonic devices are monolithically integrated [1]. In this paper, we introduce the concept of the Si/Ge/silica monolithic photonic platform and show its application to passive/active photonic device integration

2. Concept of Si/Ge/Silica monolithic photonic platform

Figure 1 shows the conceptual structure of the Si/Ge/silica monolithic photonic platform. Si photonic wire waveguides and Ge mesas grown on Si waveguides are mainly used for dynamic and active devices, which require compactness and fast operation speed, while silica waveguides are used for passive devices in which insertion loss and polarization dependence should be intensively eliminated. A Si photonic wire waveguide and a silica waveguide are connected by an inverse-taper spot size converter (SSC) [2], and the silica waveguide can serve as an interface to external optical fiber. In the Si/Ge/silica monolithic integration, it is important to deposit index-controllable silica at a low temperature so as not to damage active/dynamic devices based on Si and Ge. For this purpose, we have developed Si-rich silica (SiOx) film deposited by the electron-cyclotron-resonance plasma-enhanced chemical vapor deposition (ECR-PECVD) with a mixture gas of SiH_4 and O_2 [1]. The refractive index of SiOx can be controlled from 1.46 to 1.72 by changing the flow rate of the O_2 gas. The deposition temperature is lower than 200 ºC. Using this technology, we have developed a silica waveguide with a 3-μm-square core and an index contrast Δ of 3%. The fabricated waveguides exhibit propagation loss of about 0.6 dB/cm for infrared of 1550-nm band. This propagation loss is low enough for making a practical device on a small chip.

3. Photonic devices on Si/Ge/silica platform

On the Si/Ge/silica photonic platform, we have developed various passive and active photonic devices.

For passive devices, we have developed a 16-channel silica-based arrayed waveguide grating (AWG) in which polarization dependence could be significantly reduced[3].

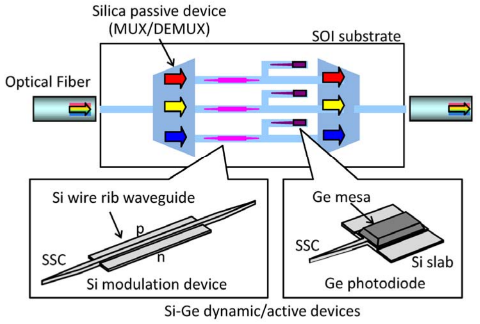
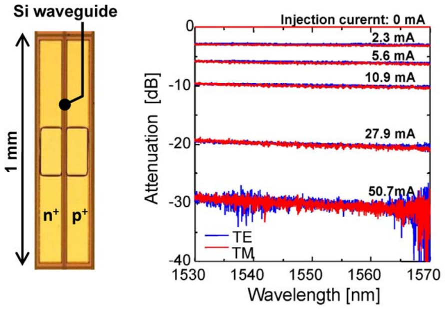
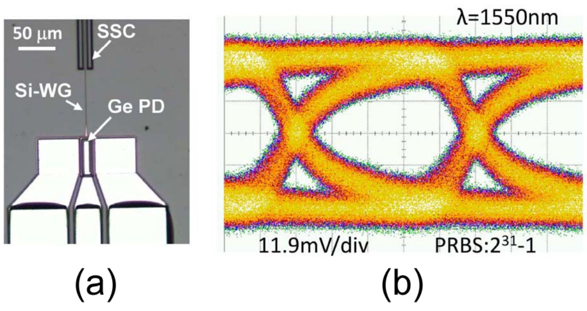


Fig. 1. Schematic of the Si/Ge/silica photonic platform.



(a) (b)

Fig. 2. (a) Top view and (b) attenuation performance of the VOA.



(a) (b)

Fig. 3. (a) Top view of the Ge PD. (b) Eye diagram of Ge-PD output in 10 Gbps receiver operation (PRBS 2^{31}-1).

For dynamic devices, we have developed polarization independent Si variable optical attenuators (VOAs) in which p-i-n carrier injection structure has been implemented in Si photonic wire waveguides[4]. Figure 2(a) shows a top view of the VOA and Fig. 2(b) shows the attenuation performance and polarization dependent loss (PDL) of a stand-alone VOA connected to silica waveguides for SSCs. As injected current increases, the attenuation of both the TE and TM modes decreases with a small difference. The dynamic range of the VOA is over 30 dB, and frequency response is around 100 MHz. The device can also work as a fast optical modulator in a few ten GHz region by applying pre-emphasized driving signals.

For active devices, we have developed Ge photodetectors (PDs) connected with a silica waveguide. Figure 3(a) shows a top view of the Ge-PD. The devices has a simple vertical p-i-n diode structure with a Ge mesa grown on a Si slab. The thickness and area of the Ge mesa are 1 μm and 8 x 50 μm^2, respectively. Typical responsivity and dark current are about 1A/W and about 100 nA, respectively. The 3-dB frequency bandwidth reaches 20 GHz, which allows a 10-Gbps optical receiver operation, as shown in Fig. 3(c).

4. Photonic device integration

Figure 4 shows a monolithic integration of 16-channel silica AWG and Si VOAs[5]. The VOA is the same as that described above. The AWG is designed for a wavelength demultiplexing with 200-GHz channel spacing. Each output port of the AWG is connected to a Si VOA. This device allows high-speed power-level adjustment in individual wavelength channels. The polarization-dependent wavelength shift (PDλ) is 0.15 nm, the crosstalk is about 20 dB.

Figure 5(a) shows a monolithic integration of a 16-channel silica AWG and Ge PDs [6]. Each output of the AWG is connected to a Ge PD via an SSC with low loss and low reflection. Figure 4(b) shows the photocurrent spectrum of the Ge PDs connected to the AWG. All 16 integrated Ge PDs are characterized as well. Since the design of the PD in this AWG integration is not optimized for high-speed operation, 3-dB frequency bandwidth is limited around 2 GHz. By optimizing the design of electrodes and carrier-doping profile, frequency bandwidth can be increased to over 20 GHz.

3. Electronics integration on photonic platform

The Si/Ge/silica photonic platform is robust for back-end electronic assembly. Moreover, no hermetic package is needed for Si, silica, and Ge photonic devices. Thus, we recently tried to integrate a 12-channel transimpedance amplifier and limiting amplifier (TIA/LA) on the AWG-PD integrated device using flip-chip bonding technology [6]. Figure 5(a) shows the top view of an integrated device. The footprint is about 1 x 1.2 cm^2. Figure 6(b) shows an output eye diagram obtained through the integrated TIA/LA receiving demultiplexed signal from the photonic chip. We confirmed successful integration of the TIA/LA on the silicon-silica photonic device and detection of the signal at all channels.

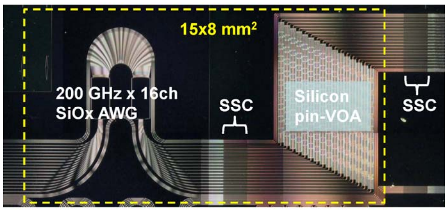
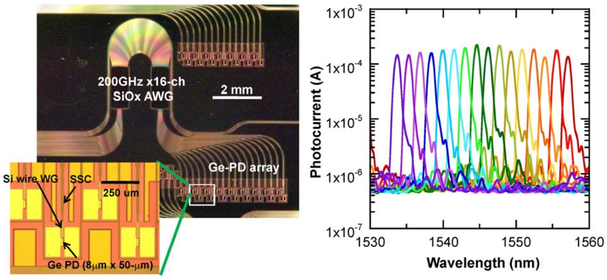
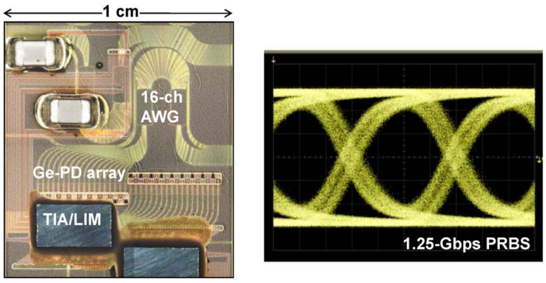


Fig. 4. Integration of silica AWG and Si VOAs.



(a) (b)

Fig. 5. (a) Integration of silica AWG and Ge photodiodes.
(b) Photocurrent spectra of 16-ch Ge photodiodes.



(a) (b)

Fig. 5. (a) Hybrid integration of TIA/LA on AWG-PD chip. (b) Eye diagram of TIA/LA output (1.25-Gbps, PRBS 2^{31}-1).

5. Summary

We have developed a Si/Ge/silica monolithic photonic integration platform for telecommunications applications and demonstrated compact AWG-VOA and AWG-PD monolithic integration. We have also demonstrated hybrid integration of electronic circuits on this photonic platform. These compact, high-functionality photonic devices could significantly reduce cost and power consumption of telecommunications modules in the future.

References

[1] T. Tsuchizawa et al., IEEE J. Sel. Topics in Quantum Electron. 17 (2011) 516.
[2] T. Tsuchizawa et al., IEEE J. Sel. Top. Quant. Electron. 11 (2005) 232.
[3] T. Tsuchizawa et al., IPR 2012, Colorado Springs (2012)
[4] H. Nishi et al., Jpn. J. Appl. Phys. 49 (2010) 04DG20.
[5] H. Nishi et al., Appl. Phys. Express 3 (2010) 102203.
[6] H. Nishi et al., Optics Express 20 (2012) 9312