Silicon photonics platforms for optical communication systems, outlook on future developments

Hiroyuki Tsuda1, a)

Abstract This paper reviews recent progress in silicon photonics and compares it with other optical device platforms. The key components for optical communication systems, including arrayed waveguide gratings, optical switches, modulators and optical functional devices fabricated on silicon photonics platforms are explained. The integration of III-V compounds, lithium niobate, polymers, phase change and other functional materials are necessary to strengthen silicon photonics platforms. These are also reviewed, and the feasibilities are discussed. Finally, I express my personal view as to the best research direction for silicon photonics.

Keywords: silicon photonics, planar lightwave circuit, III-V compounds, lithium niobate, polymers, phase change and other functional materials.

Classification: Integrated optoelectronics (lasers and optoelectronic devices, silicon photonics, planar lightwave circuits, polymer optical circuits, etc.)

1. Introduction

Photonic functional devices, in particular, wavelength multi/demultiplexers, modulators, switches, laser diodes and photo diodes play key roles in optical communication systems. InP and silica platforms have been researched since the 1980s, achieving high performance integrated optical devices. Almost all kinds of device can be integrated on an InP substrate including a light source and a detector. An analog coherent receiver, for which a DFB laser, a photo diode and a coupler were integrated on an InP substrate, was fabricated by H. Takeuchi et al. in 1989 [1]. Since then, there have been remarkable improvements in monolithic integration technologies [2]. Recently, much larger scale, monolithically integrated devices have been developed [3, 4]. For example, a 1.6-Tbps coherent 2-channel transceiver has been fabricated on an InP platform [5]. On the other hand, high performance passive optical devices such as arrayed-waveguide gratings (AWG), splitters, and optical switches have been fabricated on a silica platform. M. Kawachi et al. developed a fabrication process for a silica planar lightwave circuit (PLC) using the flame hydrolysis deposition (FHD) method, which is suitable for mass production [6]. Various PLCs have been developed and [7] are in practical use. One of the most successful devices is the AWG, which is the enabling technology for wavelength division multiplexing (WDM) transmission systems. The concept of the AWG was proposed by H. Takahashi et al. [8]. Around the same time, optical phase arrays were proposed by M. K. Smit [9] and a fully integrated AWG was fabricated by C. Dragone et al. [10]. Silica PLC technologies made steady progress and are used to make various optical components [11, 12, 13]. These platforms were technically and commercially successful and many products have been installed in actual optical communication systems.

Silicon photonics with nanowire waveguides emerged around 2000, along with the development of ultra-fine LSI fabrication technology [14, 15]. The traditional silicon optical waveguide which has a rib structure with a large core size of several µm is not compatible with CMOS fabrication processes. In contrast, the fabrication processes for silicon nanowire waveguides are almost compatible with them. This raised the expectation for the integration of optical devices with electronic devices and cost-effective mass production. However, the strong optical confinement in silicon wire waveguides raises several issues; there are larger propagation losses and phase errors in the waveguides, and the silicon itself has insufficient optical gain for lasing. Much research has been undertaken to overcome these drawbacks and to improve the silicon photonics platform by integration with functional materials.

In this paper, state of art silicon photonics devices are reviewed from several aspects, are compared to the existing platforms, and the future direction in the development of silicon photonics is discussed.

2. Passive optical devices

Table I summarize the characteristics of AWGs [16, 17, 18, 19, 20, 21, 22, 23]. Silica based commercial AWGs have excellent low-loss, polarization independent, and low crosstalk characteristics. The performance of silicon AWG is clearly inferior. Several structural improvements have been introduced; wide, multimode waveguides were used in a waveguide array to forestall the effects of sidewall roughness, and a low-loss and low-reflection structure was used at the boundary of the slab waveguide and the waveguide array. However, the performance was still insufficient for most WDM applications. Crosstalk in an AWG is mainly determined by the phase error induced by fluctuations in the core width and height [24].

Fig. 1 shows the crosstalk as a function of the silicon...
Crosstalk of less than 0.2 nm to achieve sufficiently low 100-GHz spacing. This suggests that the sidewall roughness for an 8-channel AWG with silica AWG and a silicon AWG with phase error compensation [22, 23], which suggests that we can improve the silicon AWG characteristics by using finer fabrication processes or developing efficient phase error trimming methods. One of the present solutions used to improve the crosstalk characteristics is to connect a second filter to remove crosstalk [24]. We proposed the use of a Bragg grating filter for the second filter because the filtering performance is relatively immune to the sidewall roughness [26].

Silicon photonic devices with wire waveguides are polarization dependent, therefore, a polarization diversity configuration is necessary for the devices used in inline and receiving applications. The key components are a polarization splitter and a polarization rotator. A polarization splitter-rotator, which provides both functions, has been reported [27, 28], and one such device with an extinction ratio of 20 dB, a loss of 1.5 dB, and operating in the wavelength range of 1547-1597 nm has also been reported [29].

Low loss coupling of the silicon photonic circuit to the input/output optical fiber arrays is also a significant issue. Grating couplers are easy to fabricate; however, the coupling loss cannot be reduced without multi-level etching of the silicon layer. Moreover, they have strong wavelength dependence. Therefore, grating couplers are not feasible for practical applications. As for edge coupling, a spot size converter (SSC) is necessary to reduce the coupling loss because the difference between the mode field diameter of a silicon wire waveguide and that of a standard single mode fiber is very large. The simple inverted taper type SSC has a mode field diameter of about 4 μm, and the coupling loss is about 5 dB to the standard fiber, so a more advanced structure is required for lower coupling loss. A coupling loss of 1.4 ~ 1.6 dB was achieved using a SiO₂-ZrO₂ core PLC chip between a silicon photonic chip and a fiber array [30]. Recently, a silicon nitride waveguide (SiN) combined with a silicon inverted taper SSC was reported as having a very low loss of less than 0.25 dB for the TE mode [31].

### 3. Optical switches

Free space optical switches have been installed in commercial systems; these use piezo-electric actuators, liquid crystal on silicon (LCOS) spatial modulators, or two-dimensional arrayed mirrors with micro electro-mechanical systems (MEMS), as switching engines. On the other hand, research on waveguide type optical switches has been going on for a long time because they are fast and compact. An 8×8 lithium niobate (LN) optical switch was fabricated and demonstrated in a switching network; however, it was not commercialized due to the large insertion loss, polarization dependency, high driving voltage and higher crosstalk [32]. Lanthanum doped lead zirconium titanate (PLZT) has a larger electro-optic coefficient and is suitable for optical switches. PLZT waveguide-based switches [33, 34] have switching times of several ns and are small compared to LN switches. A silica based 32×32 matrix switch was reported in 2006, and this had an average loss of 6.6 dB with an extinction ratio of 55 dB, and a polarization dependent loss of less than 0.5 dB [35]. This silica matrix switch had superior optical characteristics; however, the chip size was large, 110 mm × 115 mm, and it had much higher power consumption. Silicon photonic switches can have a big impact. A 32×32 single chip silicon photonic switch was developed by AIST [36, 37, 38]. The size was only 11 mm × 25 mm. The average loss and standard deviation were 10.8 dB, and 0.54 dB, respectively, while the average crosstalk was less than –20 dB, and the operating wavelength range was 3.5 nm. The authors also reported on a polarization diversity 32×32 switch using a SiN overlap layer to reduce waveguide crosstalks [39]. The unit switch was a Mach-Zehnder interferometer (MZI) with thermo-optic phase shifters on both arms. The switching time was about 30 μs, which is much shorter than the 0.7 ms of the silica thermo-optic switch response time. The waveguide MEMS based large-scale optical switch was invented by Prof. Ming C Wu et al. [40]. The unit switch has very low losses of 0.32 dB for the TE mode and 0.71 dB for TM mode, low crosstalk of less than –60 dB with a switching speed of 46 μs. One of the draw-

---

### Table 1 AWG characteristics

| Platform | Number of channels | Channel spacing (GHz) | Loss (dB) | Crosstalk (dB) | Polarization dependency | Remark | Reference |
|----------|--------------------|-----------------------|-----------|---------------|------------------------|--------|-----------|
| Si       | 40                 | 25                    | 3.0       | <0.2          | <0.4 dB                | Commercial, rapid, low cost | NTT Electronics Corporation Products |
| Si       | 8                  | 100                   | 1.2       | <1.6          | -                      | Reflective | [18]     |
| Si       | 25                 | 100                   | 9.0       | <1.5          | -                      | -       | [19]     |
| Si       | 15                 | 400                   | 3.5       | <2.4          | -                      | Reflective | [20]     |
| Si       | 15                 | 100                   | 5.0       | <4.0          | -                      | Reflective | [19]     |
| Si       | 15                 | 200                   | 1.0       | <2.4          | -                      | -       | [19]     |
| Si       | 15                 | 400                   | 1.7       | <2.4          | -                      | -       | [19]     |
| Si       | 15                 | 800                   | 1.8       | <2.4          | -                      | -       | [19]     |
| SiN      | 18                 | 25                    | 2.1       | <2.4          | -                      | Phase error compensated | [17]     |
| Si       | 11                 | 1                     | 19-18     | <1.8          | -                      | Phase error compensated | [21]     |
| Si       | 16                 | 1                     | 8.0       | <2.4          | -                      | Phase error compensated | [22]     |

---

![Fig. 1](image_url)  
Crosstalk of 8-channel, 100-GHz spacing AWG as a function of the silicon waveguide sidewall roughness.
backs is the high driving voltage of about 30 V. Recently, they reported on a 240 × 240 optical switch by connecting together 9 dies each with an 80 × 80 switch although wiring of the electrodes was challenging [41]. They also improved the switch characteristics; the loss of the unit switch was 0.004 dB, the crosstalk was 70 dB, and the switching time was less than 400 ns.

One of the most useful applications for optical switches is wavelength selective switching in an optical add/drop multiplexer. We have developed a silica based 1 × 4 wavelength selective switch (WSS), which has 40 channels with a spacing of 100 GHz [42]. The transmission loss and highest cross talk were 8.8 dB and −19.4 dB, respectively. The size of the chip was 116 mm × 96 mm although the loop back configuration was used to reduce the size. A silicon photonic 1 × 2 WSS using a silicon MZI switch in combination with SiN AWGs was reported by C. R. Doerr et al [43].

Conventional free-space optical switches and WSSs are bulky; however, they are low loss, have low crosstalk and are polarization insensitive. Even mature silica optical switches cannot compete for commercial applications. As mentioned above, there has been a lot of research on silicon photonic optical switches and while the performance of these devices has been improved, it is still insufficient for commercial use. If the loss and the crosstalk can be reduced to less than 5 dB and −35 dB, respectively, and they have small polarization dependence and a wide spectral range, silicon photonic switches will become a viable product, and higher speed network reconfigurations will become available.

4. Modulators

Research into various types of silicon photonic modulators has been undertaken and modulation speeds of more than several tens of Gbit/s have been realized. Such high speeds are required for the more recent optical transmission systems. A MZI modulator with pn phase shifters with 50-ohm termination travelling wave electrodes is usually provided in the process design kits (PDK) of foundry services. A MZI modulator with a $V_L$-product (where $V_L$ is the phase shift voltage, and $L$ is the phase shifter length) of 31.2 Vmm and an $\alpha V_L$-product (where $\alpha$ is the waveguide propagation loss coefficient) of 27.5 VdB was fabricated and operated at 25 Gbit/s [48]. A segmented structure was proposed to reduce the driving voltage and power consumption [49]. Although the electrical driving signals should be synchronized to the light propagating through the optical MZI waveguide, the modulator can be driven using small inverter-based circuitry. A very efficient modulator with an integrated RC equalizer was reported [50]. This had a $V_L$-product of 1.9 Vmm and operated at 56 Gbit/s. A ring resonator type modulator with compensation for its nonlinear modulating characteristics has also been developed [51]. A 112 Gbit/s PAM4 modulator was demonstrated. The size was only 10 μm in radius, and the operating wavelength could be tuned using an integrated silicon heater in the ring waveguide.
The major advantage is the simple driving method without a traveling wave electrode. A compact modulator with photonic crystal waveguides was also reported, in which the phase shifter length was 200 μm. This had a wider operating wavelength range compared to that of the ring-resonator type modulator [52, 53]. Monolithic integration of a driving circuit on a BiCMOS platform with a MZI modulator operating at 74 Gbit/s has been reported [54]. Integration of the drivers helps reduce parasitics and improve the characteristics. The modulation characteristics are mainly determined by the intrinsic silicon properties and structures used to balance trade-offs including the driving voltage, the propagation loss, and the operating electrical bandwidth and wavelength range. To improve the performance, other functional materials need to be integrated as explained in the following sections.

5. Active component integration

The indirect bandgap of silicon means it has insufficient optical gain to make a laser. Research on integration with III-V semiconductors has been done in order to realize a laser diode and an optical amplifier on a silicon photonics platform. The coupling loss between the chip and the fiber array is larger than that of other platforms, therefore, integration of active components is strongly required.

One form of integration is to solder small laser chips at the side of or onto the silicon optical circuit, as shown in Fig. 3(a). The lasers can be fabricated independently, and the performance and reliability are guaranteed. However, large scale integration and cost reduction are very difficult. Quantum dot lasers have been flip-chip bonded and coupled to a silicon photonic circuit through trident spot size converters [55]. It should be noted that a quantum dot active layer is suitable for integration with silicon because it can be operated at high temperature [56]. A semiconductor optical amplifier (SOA) was flip-chip bonded to compensate for the losses in silicon photonic switches [57, 58].

Another method is hybrid integration, where a whole or part of a III-V semiconductor wafer is bonded, as shown in Fig. 3(b). In the late 1990s, vertical cavity surface emitting lasers and photo diodes had already been successfully integrated on a silicon substrate with CMOS drivers, receivers and switches using polyimide as the adhesive material [59]. The device was operated at 311 Mbit/s which was limited by the 0.8-μm CMOS circuit performance. The drawback of using a thick adhesive material is the high thermal resistance. To overcome this problem, direct bonding was developed by S. Matsuo et al. [60]. They also proposed the use of thin III-V layers with a thickness of less than the critical value to improve the quality of the III-V layer and the reliability. This layer alleviates the problem caused by the difference in thermal expansion coefficients of the silicon wafer and the III-V layer. Phase shifters using an InGaAsP membrane and SOAs have been integrated in silicon photonic waveguides [61, 62]. Compensation for the propagation loss was provided, and the phase shifter was modulated at 40 Gbit/s.

A third method is monolithic integration of III-V layers onto silicon wafers, as shown in Fig. 3(c). Monolithic InP based lasers integrated on a silicon substrate had already been reported in the 1990s. An InGaAsP laser was fabricated on a silicon substrate, and room temperature operation at a wavelength of around 1500 nm was demonstrated [63]. III-V crystal growth requires high temperatures of more than 600 degrees, and the electrical circuit cannot survive this temperature. A low temperature growth technique is needed, but this is very difficult to do.

6. Functional material integration

New functions and superior characteristics can be realized by introducing other materials, including LN, graphene, organic materials or phase-change materials (PCM). A 120-Gbit/s PAM-4 electro-optic modulator using LN on silicon was reported by Shihao Sun et al. [64]. This had a $V_L$-product of 27 Vmm with an insertion loss of 2 dB. The dry etched LN waveguides were vertically coupled to the silicon waveguides. The hybrid substrate was fabricated by bonding an LN membrane onto a SOI wafer with benzocyclobuten (BCB) adhesive [65]. A graphene on silicon electro-absorption modulator operating up to 50 Gbit/s was reported by Vito Sorianello et al [66, 67]. They also fabricated a MZI intensity modulator, in which the phase modulator section had a $V_L$-product of 2.8 Vmm. A high-speed
Table II  Optical switch characteristics

| Material       | Mechanism        | Switching time | Index change | Self-holding characteristics |
|----------------|------------------|----------------|--------------|-----------------------------|
| LiNbO₃         | Electro-optic    | 10 ns          | 0.10%        | -                           |
| Si-III-V       | Plasma effect    | n/a            | 0.30%        | -                           |
| SiO₂           | Thermo-optic     | n/a            | 0.10%        | -                           |
| Si             | Thermo-optic     | n/a            | 0.10%        | -                           |
| Phase change   | Phase change     | 100 ns         | > 30%        | -                           |

modulator was also realized using an electro-optic organic material. The organic material was inserted into a silicon slot waveguide to have a large field overlap, and a low $V_L$-product of 0.32 Vmm with a low loss of $V_L$-product of 1.2 VdB was achieved [68]. A MZI intensity modulator using the organic material was operated up to 40 Gbit/s. Moreover, III-V materials can also improve the modulator characteristics [69]. Wafer bonding of InGaAsP using Al₂O₃ as an intermediate layer has been done, producing a phase shifter with an efficient $V_L$-product of 1.2 Vmm [70].

PCM has been widely used in optical disc recording technology such as in BD-RE (Blu-ray disc rewritable). There is a large change in refractive index between the amorphous and the crystalline states of PCM, and those states are both stable at room temperature. Table II compares the characteristics of switches using different materials.

The refractive index difference between the crystalline and amorphous states is usually more than 30%, therefore, the size of the switch can be very small. The power consumption of a PCM optical switch is very small because of its self-holding characteristics. The two states can be changed reversibly using optical pulses with different intensity and width. An optical switch using Ge₂Sb₂Te₅ (GST225) was proposed and demonstrated by H. Tsuda et al. [71, 72]. The switch has a GST225 film with a diameter of only 1 µm and a thickness of 30 nm on the silicon waveguide [73], as shown in Fig. 4(a) and 4(b). The PCM gate switch was operated with rise and fall times of 130 ns and 400 ns, respectively, and more than 2000 switching cycles were demonstrated, as shown in Fig. 5(a) and 5(b) [73]. A MZI based PCM switch and an electrically driven PCM switch were also fabricated and demonstrated [74, 75]. To improve the switching characteristics the absorption in the PCM in the crystalline state needs to be decreased. Absorption in GeSbSeTe (GSST) is smaller than that in the GST alloy [76]. A low-loss optical switch was fabricated using GSST [77].

7. Conclusion

Various improvements in silicon photonics have been achieved in recent years; however, research on integration of silicon photonics with electronics is still immature. Integration with electronics will provide important functions; performance monitoring, parameter adjustment, and dynamic control. It may also relax the fabrication error tolerances. Integrated devices will be intelligent and operated automatically at the best tuning point depending on the environmental conditions. The best approach is to continue the research on integration of silicon photonics with CMOS. In addition, integration of functional materials with CMOS compatible processes is also key to gaining an advantage over other platforms. In particular, integration with III-V materials provides optical gain on a silicon photonics platform. In conclusion, there is room for improving the performance
and reducing the fabrication and assembly costs of devices on silicon photonics platforms, and, with further research, silicon photonics will certainly become the dominant optical component platform.

References

[1] H. Takeuchi, et al.: “Monolithic integrated coherent receiver on InP substrate,” Photon. Technol. Lett. 1 (1989) 398 (DOI: 10.1109/68.43392).

[2] T. Tanemura, et al.: “Large-capacity compact optical buffer based on InP integrated phased-array switch and coiled fiber delay lines,” J. Lightw. Technol. 29 (2011) 596 (DOI: 10.1109/JLT.2010.2102338).

[3] G.E. Hoeffer, et al.: “Foundry development of system-on-chip InP-based photonic integrated circuits,” J. Sel. Top. Quantum Electron. 25 (2019) 610317 (DOI: 10.1109/JSTQE.2019.2906270).

[4] R. Gowing, et al.: “4×600 Gb/s photonic IC transmitter and receiver modules,” 2018 European Conference on Optical Communication (2018) (DOI: 10.1109/ECOC.2018.8535187).

[5] V. Lal, et al.: “1.6 Tb/s coherent 2-channel transceiver using a monolithic Tx/Rx InP PIC and a single SiGe ASIC,” Optical Fiber Communication Conference (OFC) 2020, OSA Technical Digest (2020) M3.A.2 (DOI: 10.1109/OFC.2020.M3.A.2).

[6] M. Kawachi, et al.: “Fabrication of SiO2-TiO2 glass planar optical waveguides by flame hydrolysis deposition,” Electron. Lett. 19 (1983) 383 (DOI: 10.1049/el:19830398).

[7] N. Takato, et al.: “Silica-based single-mode waveguides on silicon and their application to guided-wave optical interferometers,” J. Lightw. Technol. 6 (1988) 1003 (DOI: 10.1109/60.40941).

[8] H. Takahashi, et al.: “Arrayed-waveguide grating for wavelength division multi/demultiplexer with nanometre resolution,” Electron. Lett. 26 (1990) 87 (DOI: 10.1049/el:19900058).

[9] M.K. Smit: “New focusing and dispersive planar component based on an optical phased array,” Electron. Lett. 24 (1988) 385 (DOI: 10.1049/el:19880260).

[10] C. Dragne, et al.: “Integrated optics N×N multiplexer on silicon,” Photon. Technol. Lett. 3 (1991) 896 (DOI: 10.1109/68.93254).

[11] T. Miyazaki: “Silica-based planar lightwave circuits: passive and thermally active devices,” J. Sel. Top. Quantum Electron. 6 (2000) 38 (DOI: 10.1109/60.826871).

[12] A. Himeno, et al.: “Silica-based planar lightwave circuits,” J. Sel. Top. Quantum Electron. 4 (1998) 913 (DOI: 10.1109/60.736076).

[13] M. Takahashi, et al.: “Compact and low-loss coherent mixer based on high Δ ZrO2-SiO2 PLC,” J. Lightw. Technol. 32 (2014) 3081 (DOI: 10.1109/JLT.2014.2338914).

[14] A. Sakai, et al.: “Propagation characteristics of ultrahigh-Δ optical waveguide on silicon-on-insulator substrate,” Jpn. J. Appl. Phys. 40 (2001) L83 (DOI: 10.1143/JAP.40.L83).

[15] T. Horikawa, et al.: “A 300-nm silicon photonics platform for largescale device integration,” J. Sel. Top. Quantum Electron. 24 (2018) 8200415 (DOI: 10.1109/JSTQE.2018.2819983).

[16] K. Okamoto and K. Ishida: “Fabrication of silicon reflection-type polarization rotator-splitters in standard active silicon photonics platforms,” Opt. Express 22 (2014) 3779 (DOI: 10.1364/OE.22.003777).

[17] T. Takahashi, et al.: “Low-loss, low-crosstalk, and large-scale optical switch,” 21st OptoElectronics and Communications Conference (2016) PD2–3.

[18] K. Suzuki, et al.: “Novel concept for ultracompact polarization splitter-rotator based on silicon nanowires,” Opt. Express 19 (2011) 10940 (DOI: 10.1364/OE.19.010940).

[19] D. Dai and J.E. Bowers: “Novel concept for ultracompact polarization splitter-rotator based on silicon nanowires,” Opt. Express 19 (2011) 10940 (DOI: 10.1364/OE.19.010940).

[20] W.D. Sacher, et al.: “Polarization rotator-splitters in standard active silicon photonics platforms,” Opt. Express 22 (2014) 3779 (DOI: 10.1364/OE.22.003777).

[21] Y. Maegami, et al.: “Simple and fully CMOS-compatible low-loss fiber coupling structure for a silicon photonics platform,” Opt. Lett. 45 (2020) 2905 (DOI: 10.1364/OL.388267).

[22] P. Granstrand, et al.: “Pigtailed tree-structured 8×8 LiNbO2 switch matrix with 112 digital optical switches,” Photon. Technol. Lett. 6 (1994) 71 (DOI: 10.1109/68.265893).

[23] H. Asakura, et al.: “High-speed wavelength selective operation of PLZT-based arrayed-waveguide grating,” Electron. Lett. 48 (2012) 1009 (DOI: 10.1049/el.2012.1292).

[24] K. Kashimoto, et al.: “Nano-second response, polarization insensitive and low-power consumption PLZT 4×4 matrix optical switch,” 2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (2011) OThD3 (DOI: 10.1109/OFC.2011.OThD3).

[25] S. Sohma, et al.: “Silica-based PLC type 32×32 optical matrix switch,” European Conference on Optical Communications (2006) Tu4.4.3 (DOI: 10.1109/ECOC.2006.4801113).

[26] K. Tanizawa, et al.: “Silicon photonic 32×32 strictly-non-blocking blade switch and its full path characterization,” 21st OptoElectronics and Communications Conference (2016) PD2–3.

[27] K. Suzuki, et al.: “Low-loss, low-crosstalk, and large-scale optical switch based on silicon photonics,” J. Lightw. Technol. 38 (2020) 233 (DOI: 10.1109/JLT.2019.2934768).

[28] K. Suzuki, et al.: “Low-insertion-loss and power-efficient 32×32 silicon photonics switch with extremely high-Δ silica PLC connector,” J. Lightw. Technol. 37 (2019) 116 (DOI: 10.1109/JLT.2018.2867575).

[29] K. Suzuki, et al.: “Non-duplicate polarization-diversity 32×32 silicon photonics switch based on a SiN/Si double-layer platform,” J. Lightw. Technol. 38 (2020) 226 (DOI: 10.1109/JLT.2019.2934763).

[30] T.J. Seok, et al.: “Wafer-scale silicon photonic switches beyond die size limit,” Optica 6 (2019) 490 (DOI: 10.1364/OPTICA.6.000490).

[31] S. Han, et al.: “Large-scale polarization-insensitive silicon photonic MEMS switches,” J. Lightw. Technol. 36 (2018) 1824 (DOI: 10.1109/JLT.2018.2791502).

[32] T. Yoshida, et al.: “Switching characteristics of a 100-GHz-spacing integrated 40×1 1×4 wavelength selective switch,” Photon. Technol. Lett. 26 (2014) 451 (DOI: 10.1109/LPT.2013.2293847).

[33] C.R. Doerr, et al.: “Monolithic flexible-grid 1×2 wavelength-selective switch in silicon photonics,” J. Lightw. Technol. 30 (2012) 473 (DOI: 10.1109/JLT.2011.2173557).
Hetero structure laser emitting at 1.55 μm on a Si substrate fabricated by regrowth of InP using bonded active layer,” Opt. Express 22 (2014) 12139 (DOI: 10.1364/OE.22.012139).

T. Nakahara, et al.: “Hybrid integration of smart pixels by using polysilide bonding: demonstration of a GaAs p-i-n photodiode/CMOS receiver,” J. Sel. Top. Quantum Electron. 27 (2020) 509 (DOI: 10.1063/1.5965950).

V. Sorianello et al.: “Room-temperature operation of an InGaAsP double-hetero structure laser emitting at 1.55 μm on a Si substrate,” Appl. Phys. Lett. 57 (1990) 593 (DOI: 10.1063/1.103608).

S. Sun et al.: “120 Gbs⁻¹ hybrid silicon and lithium niobate modulators with on-chip termination resistor,” 2020 Optical Fiber Communications Conference and Exhibition (OFC) (2020) M2B.7 (DOI: 10.1364/OFC.2020.M2B.7).

M. He et al.: “High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gb/s” and beyond,” Nature Photonics 13 (2019) 359 (DOI: 10.1038/s41566-019-0378-6).

V. Sorianello et al.: “Graphene on silicon modulators,” J. Lightw. Technol. 38 (2020) 2782 (DOI: 10.1109/JLT.2020.2974189).

V. Sorianello et al.: “Graphene–silicon phase modulators with giga-hertz bandwidth,” Nature Photonics 12 (2018) 44 (DOI: 10.1038/s41566-018-0071-6).

C. Kieninger et al.: “Ultra-high electro-optic activity demonstrated in a silicon-organic hybrid modulator,” Optica 5 (2018) 739 (DOI: 10.1364/OPTICA.5.000739).

M. Takenaka et al.: “III–V/Si hybrid MOS optical phase shifter for Si photonic integrated circuits,” J. Lightw. Technol. 37 (2019) 1474 (DOI: 10.1109/JLT.2019.2892752).

Q. Li et al.: “Optical phase modulators based on reverse-biased III-V/Si hybrid metal–oxide-semiconductor capacitors,” Photon. Technol. Lett. 32 (2020) 345 (DOI: 10.1109/LPT.2020.2973174).

Y. Ikuma et al.: “Proposal of a small self-holding 2×2 optical switch using phase-change material,” IEICE Electron. Express 5 (2008) 442 (DOI: 10.1587/elex.5.442).

Y. Ikuma et al.: “Small-sized optical gate switch using Ge2Sb2Te5 phase-change material integrated with a silicon waveguide,” Electron. Lett. 46 (2010) 366 (DOI: 10.1049/el.2010.3588).

D. Tanaka et al.: “Ultra-small, self-holding, optical gate switch using Ge2Sb2Te5 with a multi-mode Si waveguide,” Opt. Express 20 (2012) 10283 (DOI: 10.1364/OE.20.010283).

T. Moriya et al.: “Ultra-compact, self-holding asymmetric Mach–Zehnder interferometer switch using Ge2Sb2Te5 phase-change material,” IEICE Electron. Express 11 (2014) 20140538 (DOI: 10.1587/elex.11.20140538).

K. Kato et al.: “Current-driven phase-change optical gate switch using indium–tin–oxide heater,” Appl. Phys. Exp. 10 (2017) 072201 (DOI: 10.7567/APEX.10.072201).

A.S. Hassamen and J. Sharma: “Band-gap engineering, conduction and valence band positions of thermally evaporated amorphous Ge2Sb2Te5 thin films: influences of Sb upon some optical characteristics and physical parameters,” J. Alloys Compd. 798 (2019) 750 (DOI: 10.1016/j.jallcom.2019.05.052).

Y. Zhang et al.: “Reshaping light: reconfigurable photonics enabled by broadband low-loss optical phase change materials,” Proc. SPIE 10982, Micro- and Nanotechnology Sensors, Systems, and Applications XI (2019) 10982Q0 (DOI: 10.1117/12.2513385).

IIECE Electronics Express, Vol.17, No.22, 1–7