Ge-on-Si photonic devices for photonic-electronic integration on a Si platform

Yasuhiko Ishikawa¹a) and Shinichi Saito²b)

¹ Department of Materials Engineering, Graduate School of Engineering, The University of Tokyo, 7–3–1 Hongo, Bunkyo, Tokyo 113–8656, Japan
² Nano Research Group, Faculty of Physical Sciences and Engineering, University of Southampton, Southampton, SO17 1BJ, United Kingdom

a) y-ishikawa@material.t.u-tokyo.ac.jp
b) s.saito@soton.ac.uk

Abstract: This paper reviews near-infrared Ge photonic devices on Si towards photonic-electronic integrated circuits on a Si platform, which play a significant role in short-reach optical interconnects. In particular, applications of Ge epitaxial layers on Si to photodetectors, light emitters and optical modulators are described.

Keywords: Ge photonic devices, Si photonics, optical interconnects, photodetectors, light sources, optical modulators

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References


2008.247


[71] Q. Xu, B. Schmidt, S. Pradhan and M. Lipson: Nature 435 (2005) 325. DOI:10.1038/nature03569


1 Introduction

Si is the second most abundant element following oxygen in the crust of the earth, and is an indispensable semiconductor to support the modern information communication technologies [1]. According to the Semiconductor Industry Association [2], the global semiconductor market in 2013 exceeded 300 billion US dollars, which corresponds to more than 40 US dollars/person/year on average over all generations and countries. World Semiconductor Trade Statistics [3] reported that more than 80% of the global semiconductor market was dominated by integrated circuits, which were mostly based on Si complementary metal-oxide-semiconductor (CMOS) transistors. Figs. 1(a) and 1(b) summarize the histories/prospects for the number of transistors on a CMOS chip and the minimum feature size of transistor, respectively [4, 5]. If the scaling follows Moore’s law [6] in the next decade, the number of CMOS transistors integrated on a chip of micro-processing unit (MPU) will exceed the number of neurons (11–12 billions) in a human brain. In Fig. 1(a), the history of III-V devices [7, 8] is also plotted. It is noted that the slope for the developments of III-V devices is steeper in the late 1970’s and the early 1980’s than the trend of Moore’s law. At that time, III-V digital circuits were extensively studied due to the superior electron mobility, resulting in the operation speed higher than that for Si. However, the present market of III-V devices is much smaller than that of Si; the shares of optoelectronics and discrete semiconductor devices, dominated by III-V compounds, are as small as 9% and 6%, respectively [3]. There are several reasons to explain the historical choice of Si for electronics, e.g., scalability, high yields, high integration capabilities, readiness levels in processing, and low-power logic operation [1, 9]. Particularly, low-cost fabrication and low-power consumption possess higher priorities than high-speed operation, as systematically formulated in the blue ocean strategy [10]. Consequently, the use of III-V compounds is limited mainly to discrete components such as laser diodes in niche photonics markets, while Si is used in mass markets of consumer electronics.
Optical interconnects using III-V compounds have been applied to long-haul optical fiber communications and fiber-to-the-home communications, while Si photonics have been investigated towards a mass market of shorter-reach optical interconnects such as rack-to-rack, board-to-board, and chip-to-chip communications as well as intra-chip/inter-core communications in MPUs. In order to support rapid increase of data volumes transmitted via the internet [11], low-power optical interconnects are inevitably required with a low-cost fabrication for massive photonic components to be installed. It is noted that Si is widely selected as the base material even in such new types of optical interconnects, since low-cost fabrication and low-power consumption are rather important. Up to the middle 2000’s, Si passive photonic devices based on Si optical waveguides with the submicron cross-section were monolithically integrated using CMOS processes. However, there is a critical issue in Si photonics, i.e., how to realize active photonic functions such as photodetection and light emission as well as low-power optical intensity modulation using CMOS-compatible processes. In this review, an approach is described, where Ge, one of the group-IV semiconductors similar to Si, is utilized.

Fig. 1. Historical trends of (a) number of devices integrated on a chip and (b) minimum feature size of transistor with key technologies in each generation.
2 Properties of Ge for photonic devices

Si is an indirect bandgap semiconductor, as in Fig. 2(a), with a poor efficiency in the light emission. Photonic/optical devices of Si are limited mainly to image sensors and solar cells, where strong optical absorption in the visible range is utilized. In the near-infrared (NIR) optical communication band (1.3–1.6 µm), no optical absorption takes place in Si, as in Fig. 3(a). Instead, Si has a larger refractive index \( n \approx 3.5 \) than those for SiO\(_2\) \( n \approx 1.5 \) and air \( n = 1.0 \), as in Fig. 3(b). This property allows the application of submicron-scale channel/rib structures of Si [12, 13, 14] to single-mode NIR optical waveguides (WGs) for on-chip optical communications. The light can be strongly confined in the submicron Si core, reflecting the large contrast of refractive index with SiO\(_2\)/air cladding. Such Si WGs have been fabricated, patterning a top Si layer of Si-on-insulator (SOI) wafer with a CMOS process [13, 14, 15]. Low-loss propagation has been realized even at a bending with the radius as small as a few microns. Small sizes of ring resonators [15] and arrayed waveguide gratings (AWGs) [16] have been also realized for wavelength filters applicable to the wavelength division multiplexing (WDM) communications. These waveguide-based passive devices can be monolithically integrated on a Si platform, although there remain issues such as propagation losses due to the sidewall roughness (typically 1 dB/cm for channel WGs at present [17]) and the nanometer-scale error in WG size preventing the precise control of operation wavelengths in WDM filters.

**Fig. 2.** Schematic band structures for (a) Si and (b) Ge.

**Fig. 3.** Spectra of (a) absorption coefficients and (b) refractive indices for Si, Ge and other important materials for photonics.
Crucial issues also lie in how to realize active functions such as NIR photodetections and light emissions as well as low-power optical intensity modulations with keeping the compatibility with the CMOS fabrication process. As in Table I, various materials have been used in the long-haul fiber communications such as III-V compounds and LiNbO₃, but these materials are difficult to be introduced in the CMOS process. For the cost-effective integrations, the number of materials should be reduced as small as possible, taking into account that Si electronics is composed of a small number of materials, as also in Table I. Ge should be a promising candidate to realize active photonic functions on Si. Making the best use of optoelectronic properties in Ge described below, monolithic photonic-electronic integration on Si can be realized using the limited materials of Ge, Si and Si-based dielectrics together with metals for local electrical interconnects. It should be mentioned that the process compatibility between Ge and Si is reasonable; in electronics, GeSi alloys have been used for high-speed amplifiers as well as stressors in high-speed MOS transistors. Pure Ge has been investigated as a channel material in front-end transistors for next generations.

Ge is an indirect bandgap semiconductor similar to Si, as in Fig. 2(b). The conduction band minimum is located at the L point, where the gap energy is 0.66 eV at room temperature (RT). The important feature for photonic device applications is that the direct bandgap at the Γ point is 0.80 eV, corresponding to 1.55 µm in wavelength. A strong optical absorption occurs with the absorption coefficient more than 1000 cm⁻¹ for the wavelength below 1.55 µm, as in Fig. 3(a), being applicable to NIR photodetectors in the optical communication bands. The small energy difference of 0.14 eV between the L and Γ points in the conduction band suggests quasi-direct gap behaviors useful for active photonic device functions; an abrupt change in the optical absorption occurs at 1.55 µm, and as described later, Ge reveals a light emission around 1.55 µm due to the direct band-to-band transitions. A large electro-absorption (EA) effect is observed, being applicable to optical intensity modulations. As for the refractive property, the refractive index for Ge is as large as 4.0 in NIR, as in Fig. 3(b), which is larger

| Table I. Devices and main materials in electronics and photonics. |
|---------------------------------|------------------|------------------|
| **Device** | **Main material** |
| Electronics | MOSFET | Si, SiO₂, SiNₓ, Cu, Al |
| | Metal interconnect | |
| | Fiber communication | Si photonics |
| | Optical waveguides | SiO₂, Si, SiNₓ |
| | Multiplexer/ | SiO₂, Si, SiNₓ, SiOₓ, SiOₓNₓ |
| | demultiplexer | |
| Photonics | Photodetector | InGaAs, Ge |
| | Optical modulator | LiNbO₃, Si, Ge |
| | Light source | InGaAsP, InGaAsP ⇒ Ge |
| | Optical amplifier | SiO₂: Er ⇒ Ge (?) |
| | Optical isolator | Yttrium iron garnet (YIG) ? |
than that for Si (≈3.5). The light tends to be present in Ge at the Ge/Si interface, being useful for the evanescent coupling of light from Si WGs to Ge devices.

3 Epitaxial growth of Ge on Si and electrical properties of pin diodes

3.1 Epitaxial growth of Ge on Si

In order to apply Ge to photonic devices on Si, it is necessary to form high-quality Ge layers on Si. However, there is a large lattice mismatch of 4% between Ge and Si; in Ge epitaxial layers thicker than the critical thickness (~1 nm), threading dislocations are generated with a high density in addition to misfit dislocations at the Ge/Si interface. These defects act as unfavorable generation/recombination centers for carriers. A large surface roughness should be also induced as the result of three-dimensional Stranski-Krastanov growth. Luan et al. [18] reported that a uniform epitaxial layer of Ge is directly grown on Si (001) wafer by ultrahigh-vacuum chemical vapor deposition (UHV-CVD) with a low-high temperature (typically 350°C/600°C) two-step growth. Fig. 4(a) shows an example of cross-sectional transmission electron microscope (TEM) image for 1-µm-thick Ge layer on a (001) SOI wafer grown at the University of Tokyo by the authors. The image reveals the formation of uniform layer of Ge, although threading dislocations with the density as high as \(10^8\)–\(10^9\) cm\(^{-2}\) are generated in Ge, as in the top of Fig. 4(b). The density tends to be reduced with increasing the layer thickness [19], while a post-growth annealing at high temperatures (800–900°C) [18] is effective to reduce the threading dislocation density below \(10^8\) cm\(^{-2}\), as in the bottom of Fig. 4(b) and in Fig. 4(c).

![Image](image-url)

**Fig. 4.** (a) Cross-sectional TEM images for as-grown Ge (1 µm in thickness) on SOI wafer, (b) plan-view TEM images for as-grown and annealed Ge, and (c) threading dislocation density in Ge as a function of growth/annealing temperature.
Ge can be grown on selective areas of Si surface with SiO2 masks [18, 20, 21]. Typical optical and scanning electron microscope images taken by the authors are shown in Figs. 5(a) and 5(b), respectively. The mesa-shaped structure, surrounded with the inclined (113) facet sidewalls, is effective for the evanescent coupling of light from Si WGs [20, 21], as schematically shown at the top of Fig. 5(b).

It is noted that a tensile strain is induced in Ge grown on Si (or SOI) wafers [22, 23, 24, 25]. As in Fig. 6(a), x-ray diffraction (XRD) measurements revealed that (004) diffraction peaks from Ge layers on (001) Si showed positive shifts in the $\omega$–$2\theta$ scans in comparison with bulk Ge [25]. This indicates the decrease of out-of-plane lattice constant, i.e., the increase of in-plane lattice constant induced by a biaxial tensile strain as large as 0.1–0.3%. Although the compressive strain in Ge due to the 4% lattice mismatch should be relaxed after the growth more than the critical thickness ($\sim$1 nm), such a tensile strain is generated during the cooling from the growth/annealing temperature to RT due to the mismatch of thermal expansion coefficient between Si and Ge [22, 24]. As schematically shown in Fig. 6(b), the shrinkage of Ge lattice during the cooling is prevented by the thick Si wafer having smaller thermal expansion coefficient. It is important that the lattice strain causes the changes in the band structure for semiconductors [26]. Fig. 7(a) shows changes in the band-edge energies for Ge as a function of in-plane strain [24, 25] calculated using deformation potential values reported in Refs. [27] and [28]. Under the tensile strain, the conduction band energy at the $\Gamma$ point is decreased, while the light-hole (LH) valence band splits from the heavy-hole (HH) band, accompanying the energy increase. As a result, the direct bandgap energy is reduced as in Fig. 7(b), leading to a red shift in the optical absorption edge for the direct band-to-band transitions. This enhances the photodetection efficiency, as described later. It is also important that, if the tensile strain can be increased as large as 2%, the energy of conduction band at the direct $\Gamma$ point is reduced lower than that at the indirect L point, leading to a transition to a direct-gap semiconductor. An efficient light emission would be obtained, although the gap energy is reduced to $\sim$0.6 eV, which corresponds to the wavelength more than 2 $\mu$m favorable for the optical biosensing [29].
3.2 Electrical characteristics of Ge pin diodes on Si

Using the Ge layers on Si, a vertical structure of pin diode (Fig. 8(a)) was fabricated as the fundamental structure for the active photonic devices. Fig. 8(b) shows typical current-voltage ($I$-$V$) characteristics. A good rectifying property is obtained for the diode using the Ge layer annealed at a high temperature (800°C) after the growth. Due to the reduction of threading dislocation density by the post-growth annealing, the dark leakage current is reduced to $\sim 20$ mA/cm$^2$ at the reverse bias of 1 V. As summarized in Fig. 8(c), the dark leakage current tends to decrease with decreasing the threading dislocation density in Ge [23, 30, 31, 32, 33]. However, the high-temperature annealing to reduce the dislocation density could be eliminated from the viewpoint of compatibility with the CMOS process for electronic circuits, otherwise Ge layers need to be formed at the beginning of front-end process, causing a drastic change in the existing CMOS process. In this regard, pin diodes of as-grown Ge formed with an optimized growth sequence showed a reduced dark leakage current as small as 50 mA/cm$^2$, as in Fig. 8(b), although further decrease in the dark leakage current should be achieved.
4 Ge-on-Si photonic devices

4.1 Photodetectors

Fig. 9 shows a typical responsivity spectrum for Ge pin diodes on Si at a normal incidence of NIR light. A high-efficiency photodetection is realized in the C band (1.53–1.56 µm). Resulting from the bandgap narrowing due to the tensile strain in Ge, a red shift takes place in the responsivity spectrum, leading to a photodetection even in the L band (1.56–1.62 µm) [22, 23, 24, 25]. Ge photodetectors integrated with Si WGs, shown in Fig. 5(b), have been realized [20]. The operation frequency more than 30 GHz has been reported for such integrated devices [34, 35].

Fig. 8. (a) Schematic illustration of fabricated Ge pin diode on Si, (b) typical I-V characteristics at RT in dark, and (c) a summary of dark current density at 1-V reverse bias as a function of threading dislocation density in Ge.

Fig. 9. Typical free-space responsivity spectra for Ge pin diode on Si.
lanche photodiodes of Ge with a carrier multiplication layer of Si have been also fabricated for the highly sensitive photodetection [36]. A monolithic integration of Ge photodiodes, Si WGs and a silica-based AWG has been reported as a WDM receiver chip [17, 37]. As for the photonic-electronic integration, a photonic receiver chip monolithically integrated with Si electronics such as transimpedance amplifiers has been developed [38]. The chips have been commercially applied to active optical cables for rack-to-rack interconnects in data centers and supercomputers.

4.2 Prospects for on-chip light sources

Since there is no practical light source based on Si and group-IV materials, III-V lasers bonded on Si [39] are used as on-chip light sources in Si photonics. Recently, the use of Ge has attracted interests for the light sources monolithically integrated on Si. As schematically shown in Fig. 10(a) for low level of injection of electrons and holes (< $10^{19}$ cm$^{-3}$) in Ge, almost no light emission is obtained around 1.55 µm resulted from the direct band-to-band transition, since electrons only occupy the indirect L valley of conduction band. On the other hand, increasing the injection of carriers, where electrons also occupy the $\Gamma$ valley, as in Fig. 10(b), the light emission due to the direct transition is obtained. In fact, as in Fig. 11(a), photoluminescence (PL) measurements under a high excitation (4 mW of 457-nm laser light with $\sim$2 µm in diameter) showed a light emission around 1.55 µm from Ge layers on Si as well as from bulk Ge. Electroluminescence (EL) can be also obtained for vertical Ge pn diodes on Si under forward biases [40, 41, 42] and for lateral pn diodes of Ge fabricated with standard CMOS processes [43, 44]. Fig. 11(b) shows an example of EL spectra for a vertical pin diode. The light intensity emitted from Ge, however, is rather poor in comparison with III-V compounds; the PL intensity from Ge is smaller than that from InGaAs on InP by $\sim$4 orders of magnitude, as in Fig. 11(a). Micro-resonators of Ge [45, 46, 47] and other technologies [48, 49] have been examined to enhance the light emission, while the emission enhancement was still less than one order of magnitude. In order to increase the light emission significantly, heavily n-type doping ($>10^{19}$ cm$^{-3}$) in Ge was proposed [50]. The L valley is pre-filled by electrons with the n-type doping, and electrons can be efficiently injected to the $\Gamma$ valley of conduction band, as in Fig. 10(c). The tensile strain in Ge also helps to inject electrons efficiently in the $\Gamma$ valley [50], since the energy difference between the L and $\Gamma$ points of conduction band are reduced, as in Fig. 10(d). As a result, an enhancement of PL intensity more than one order of magnitude was obtained for the n-type doping as high as $10^{19}$ cm$^{-3}$ [51, 52]. Furthermore, such an n-type tensile-strained Ge revealed an optical gain [53]. In a Fabry-Perot resonator of Ge waveguide, a lasing was also reported under an optical pumping [54] and an electrical pumping [55, 56], although there is no further report to obtain the lasing. In order to generate a large (> 1%) tensile strain towards direct-gap Ge, an application of micromechanical stress [57] to membrane structures [58, 59, 60, 61] was examined, but no lasing has been obtained yet. Critical process techniques might be required for the laser operation, and further studies are necessary from the viewpoints of material science and device physics.
4.3 Low-power optical modulators

Optical modulators have been investigated to generate optical signal from a continuous-wave laser light. One of the basic modulators uses Mach-Zehnder interferometer (MZI) structure composed of two Si rib WGs embedding pn junction [62, 63]. Because of the crystal symmetry of Si, there is no first-order electro-optic (EO) effect (Pockels effect), while the change in the refractive index in Si can be obtained with the free-carrier plasma effect induced by the high density of carriers [64]. An injection of carriers under a forward bias [63] or a depletion of carriers by

![Diagram of optical modulators](image)

**Fig. 10.** Schematic band structures for (a) unstrained Ge with low level of carrier injection, (b) unstrained Ge with high level of carrier injection, (c) heavily n-doped unstrained Ge with low level of carrier injection, and (d) heavily n-doped tensile-strained Ge with low level of carrier injection.

![Graphs of PL and EL spectra](image)

**Fig. 11.** (a) Typical PL spectra for bulk Ge, Ge layer on Si, and InGaAs on InP, and (b) typical EL spectra for forward-biased Ge pin diode on Si.

4.3 Low-power optical modulators

Optical modulators have been investigated to generate optical signal from a continuous-wave laser light. One of the basic modulators uses Mach-Zehnder interferometer (MZI) structure composed of two Si rib WGs embedding pn junction [62, 63]. Because of the crystal symmetry of Si, there is no first-order electro-optic (EO) effect (Pockels effect), while the change in the refractive index in Si can be obtained with the free-carrier plasma effect induced by the high density of carriers [64]. An injection of carriers under a forward bias [63] or a depletion of carriers by
heavily doping under a reverse bias [62] is used to obtain the modulation of refractive index. Table II summaries the recent reports [65, 66, 67, 68, 69, 70] on the performance of Si EO modulators [65, 66, 67, 70] together with the performance of Ge-based electro-absorption (EA) modulators [68, 69] described below. In Si MZI modulators, the operation speed more than 10 Gbps has been reported with the operation spectrum width over 30 nm [63, 65, 66, 67]. However, a large energy (> ~4 pJ/bit) is consumed for modulations due to the length of devices more than 100 µm [63, 65, 66]. A reduced size of optical modulator using a Si ring/disk resonator as small as 10 µm in diameter has been reported for the reduction of energy consumption [70, 71, 72]. The energy can be reduced to be on the order of 0.1 pJ/bit or below, which is smaller by more than one order of magnitude in comparison with the MZI devices. However, for the ring/disk devices, the operation wavelength is limited only at around the resonance wavelengths. The large thermo-optic effect in Si also leads to a poor stability of resonance wavelength against temperature variations, although heaters have been implemented to stabilize the operation wavelength [73] in spite of the additional energy consumption. The use of slow light in photonic crystal WGs has been also investigated for the reduced size of Si EO modulators [74].

Another approach to realize optical modulators is to use EA effect in Ge such as Franz-Keldysh effect (FKE) [69, 75] and quantum-confined Stark effect (QCSE) [68, 76]. In both cases, the optical absorption edge is shifted towards the longer wavelength under high electric fields (typically, >10 kV/cm). The optical intensity modulation is achieved applying and removing the electric field. In FKE, electron and hole waves penetrate into the bandgap under the high electric field, as in

Table II. Summary of advanced optical modulators in Si photonics

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>MZI</th>
<th>MZI</th>
<th>MZI</th>
<th>QCSE</th>
<th>FKE</th>
<th>Disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier control</td>
<td>pn</td>
<td>MOS</td>
<td>MOS</td>
<td>pin</td>
<td>pin</td>
<td>pn</td>
</tr>
<tr>
<td>Waveguide</td>
<td>Rib</td>
<td>Rib</td>
<td>Rib</td>
<td>Rib</td>
<td>Channel</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Si</td>
<td>Poly-Si</td>
<td>Poly-Si</td>
<td>Ge QW</td>
<td>GeSi</td>
<td>Si</td>
</tr>
<tr>
<td>Spectrum width [nm]</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>22</td>
<td>35</td>
<td>0.1</td>
</tr>
<tr>
<td>Active length [µm]</td>
<td>3500</td>
<td>480</td>
<td>200</td>
<td>10</td>
<td>55</td>
<td>4</td>
</tr>
<tr>
<td>Data rate [Gbps]</td>
<td>50</td>
<td>20</td>
<td>15</td>
<td>7</td>
<td>28</td>
<td>12.5</td>
</tr>
<tr>
<td>3-dB bandwidth [GHz]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40.7</td>
<td>15</td>
</tr>
<tr>
<td>DC bias [V]</td>
<td>5</td>
<td>-</td>
<td>0</td>
<td>4</td>
<td>1.4</td>
<td>0</td>
</tr>
<tr>
<td>$V_{pp}$ [V]</td>
<td>6.5</td>
<td>-</td>
<td>1.5</td>
<td>1.0</td>
<td>2.8</td>
<td>2</td>
</tr>
<tr>
<td>DC extinction ratio [dB]</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
<td>-</td>
<td>6.0</td>
<td>-</td>
</tr>
<tr>
<td>AC extinction ratio [dB]</td>
<td>10.0</td>
<td>-</td>
<td>3.6</td>
<td>3.0</td>
<td>5.9</td>
<td>3.2</td>
</tr>
<tr>
<td>DC power [mW]</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AC power [mW]</td>
<td>845</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>AC energy [fJ/bit]</td>
<td>4,225</td>
<td>4,500</td>
<td>-</td>
<td>0.75</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Group</td>
<td>U. SOTON</td>
<td>U. Penn/CISCO</td>
<td>PETRA</td>
<td>Stanford</td>
<td>Kotura/Oracle</td>
<td>MIT/Sandia</td>
</tr>
<tr>
<td>Reference</td>
<td>[65]</td>
<td>[66]</td>
<td>[67]</td>
<td>[68]</td>
<td>[69]</td>
<td>[70]</td>
</tr>
<tr>
<td>Year</td>
<td>2013</td>
<td>2013</td>
<td>2013</td>
<td>2012</td>
<td>2012</td>
<td>2011</td>
</tr>
</tbody>
</table>
Fig. 12(a), leading to the reduction in the minimum energy for optical transitions, i.e., the red shift in the optical absorption edge. The absorption spectra reported for bulk Ge [77] under different electric fields are reproduced in Fig. 12(b). Optical absorption is extended towards longer wavelengths than the absorption edge of 1.55 µm. Similar to bulk Ge, the optical absorption is enhanced for Ge pin structures on Si under the electric field higher than 10 kV/cm, as shown in Fig. 12(c), although the absorption edge is located around 1.6 µm due to the presence of tensile strain. The change in the absorption coefficient is obtained to be more than 100 cm$^{-1}$. This corresponds to the length of modulator as small as 10 µm, being effective to reduce the energy consumption. For Ge pin structure on Si, the modulator operation around 1.6 µm has been reported [78, 79], while shorter wavelength operation around 1.55 µm has been achieved using wider-gap GeSi alloys with a few percent of Si [69, 75]. The use of SiNx stressor to compensate the tensile strain in Ge was also examined for the operation around 1.55 µm [80]. GeSi waveguide modulators with the length as small as 50 µm showed an energy consumption as small as 50 fJ/bit, the operation spectrum width as large as 14 nm, and the operation speed more than 1 Gbps [75]. In QCSE devices, Ge quantum wells sandwiched by GeSi barriers are used [76]. The absorption edge is located at shorter wavelength than that for bulk Ge due to the formation of quantized levels, being effective for the operation with the wavelengths shorter than 1.55 µm. Under high electric fields, the quantized energies for electrons and holes in the Ge wells are reduced. The optical absorption is enhanced in the wavelengths longer than the absorption edge, similar to FKE in Ge. Compared with FKE for bulk Ge, an abrupt change in the absorption coefficient takes place for
QCSE around the absorption edge due to the stepwise change in the density of states for carriers, and an extinction ratio larger than FKE is observed [68]. The optical modulation based on QCSE has been reported for the operation wavelength of 1.42–1.54 µm and the operation speed as large as 20 GHz with the power consumption on the order of 0.1 pW or below [68, 81, 82, 83, 84, 85]. For the integration with Si WGs, the thickness of relaxed SiGe buffer layer beneath the Ge/GeSi quantum wells should be reduced [84]. The operation at shorter wavelengths around 1.3 µm could be obtained with a precise control of Ge well thickness [86, 87].

5 Summary

NIR Ge-on-Si photonic devices were reviewed for photonic-electronic integration on a Si platform, which play significant roles in short-reach optical interconnects in terms of low-cost fabrication and low-power consumption with keeping high-capacity data transmission. High-quality Ge layers epitaxially-grown on Si have been successfully applied to NIR photodetectors integrated with Si WGs. Light emitters and optical modulators using Ge layers on Si were also studied to realize highly-functionalized photonic-electronic integrated circuits on a Si platform.

Yasuhiko Ishikawa
received the B.E. and M.E. degrees in electrical engineering, and the Ph.D. degree in electronics and information engineering from Hokkaido University, Sapporo, Japan, in 1993, 1995, and 1998, respectively. He is currently an Associate Professor in the Department of Materials Engineering, the University of Tokyo, Tokyo, Japan. In 2001–2002, he was a Visiting Scientist at the Materials Processing Center, Massachusetts Institute of Technology, Cambridge, USA. His current interest is Si-based photonic devices and their applications to communication and sensing systems. Dr. Ishikawa is a member of IEEE Photonics Society, the Materials Research Society, the Electrochemical Society, and the Japan Society of Applied Physics.

Shinichi Saito
completed his PhD in theoretical condensed matter physics and was a research associate at Waseda University. In 2000, he joined Hitachi Central Research Laboratory, and developed CMOS front-end process and device technologies, including high-k gate dielectrics, quantum confinements, and strain engineering. He won the SSDM paper awards for the mobility reduction mechanism in CMOS FETs with high-k dielectrics in 2003 and for stimulated light-emissions from Si fin light-emitting diodes in 2011. In 2012, he moved to the University of Southampton, UK, taking up a professorship. He is currently working for Si photonics, single electron transistors/pumps, and Si/Ge light-emitters. He is a member of JPS, JSAP, and IEICE.