Silicon- Based Photonics

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**Erich Kasper
Jinzhong Yu**

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Preface

Both authors were guest professors at the same time at the Huazhong University of Science and Technology (HUST) in Wuhan, China. The Yangtse River area around Wuhan is known in China as Optics Valley, with broad research and manufacturing activities in fiberglass, optical sensors, optoelectronic devices, and photonic systems. We were in touch before on different topics of semiconductor device physics and material science but focused during our stay in Wuhan on silicon photonics.

Silicon photonics evolved rapidly as a research topic with enormous application potential. Essentially, the following three phases were responsible for continuous progress in this research area. The large refractive index contrast of silicon-on-insulator (SOI) waveguides allowed densely packed and strongly curved waveguides on chip-size carriers in the first phase. The second phase benefitted from progress in silicon microelectronics, with high-performance foundry service available to design and system groups. In this second phase, the number of involved groups jumped up and the economic fabrication sparked the vision of integration of photonic and microelectronic systems. A fundamental problem remained: the waveguide has to be transparent in the used infrared wavelength regime, but for conversion of the electrical signal in an optical one and vice versa, a strong light-matter interaction is requested. In the third phase, this photonics problem is tackled with semiconductor heterostructure devices where the heterostructure partner offers a higher cutoff wavelength as silicon.

We felt that the settled first two phases are well treated in monographs and edited books on silicon photonics whereas the reader has to consult proceeding volumes to monitor the rapid progress of the third phase.

We tried in the given book, titled *Silicon-Based Photonics*, to merge a concise treatment of classical silicon photonics with the description of principles, prospects, challenges, and technical solution paths of adding silicon-based heterostructures.

We acknowledge the help of many colleagues with whom we discussed different topics at common conference meetings and at personal meetings. Substantial contributions to the design of text and graphics of various chapters were made by Michael Oehme, Xuejun Xu, Kang Xiong, Qingzhong Huang, Xi Xiao, Yingtao Hu, Yuntao Li, Hejun Yu, Zhiyong Li, Hao Xu, and Yu Zhu.

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Erich Kasper

Jinzhong Yu

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Chapter 1

Introduction

Who are the technical parents of silicon photonics? Undoubtedly, the long-lasting technological success of silicon microelectronics, with their high integration levels on one side and the complete replacement of long-distance wire communication by optical fiber glass transmission on the other side, nurtured the demand to join optical waveguide transmission and reliable system integration on a silicon wafer scale. The pioneers (e.g., Soref and Lorenzo [1], Petermann [2], and Abstreiter [3]) proposed in the 1980s and the early 1990s waveguide and optoelectronic device integration on silicon although the indirect semiconductor silicon was considered as less favorable for optical functions. Indeed, the device and circuit development in microelectronics and optoelectronics started in different directions. Focus [4] on a basically simple device type (metal oxide semiconductor transistor) and on a few materials for the technology (semiconductor Si, dielectrics SiO₂, metal Al) made circuit design and integration in microelectronics easy. Progress in device and circuit performance was achieved by shrinkage of the device dimensions. This period of microelectronics, named “dimension scaling,” lasted from the beginning of integrated circuit manufacturing (around the year 1975) to about the years 2000–2005. In optoelectronics, the performance was driven by sophisticated heterostructures based on III/V semiconductors that had excellent absorption, emission, and modulation properties for

optical signals. At this time (around the year 2000) it was clear that telecommunication was governed at far distances (more than 10 km) by optical signal transmission and at near distances by electrical signals. Near distances meant distances within an enterprise (0.1–10 km), between racks (1–100 m), between boards (10–100 cm), between chips (1–10 cm), and on a chip (<1 cm). With increasing speed (3–10 GHz), the optical communication was predicted to be competitive also at near distances because electrical connections suffer from the resistance-capacitance (RC) limitation of the speed of interconnects. Irrespective of the speed of devices, the speed of electronic circuits is ultimately limited by the interconnect time delay that is inversely proportional to the RC product.

1.1 Si Photonics

Silicon (Si) photonics is the prime candidate to cover the application range at the border region between pure electrical and pure optical solutions. The essential property of planar Si waveguides is due to their high refractive index contrast when fabricated on silicon-on-insulator (SOI) substrates (Fig. 1.1). These commercially available SOI substrates are composed of a Si wafer with a thin (typically 1 μm) SiO_2 (insulator) layer and an even thinner (typically 0.2–0.4 μm) Si layer on top.

The waveguide formation along a lithographically defined pattern uses etching (mainly dry etching by a reactive gas). Ridge waveguides show in cross section a ridge (Fig. 1.1, left side) on a partially etched Si top layer surrounding. The waveguide of small dimensions is called a nanowire if the complete Si layer outside the waveguide is etched (Fig. 1.1, right side). The waveguide core from a semiconductor like Si has a high refractive index n (about 3.5). The cladding from glass has a much lower refractive index, of about 1.5. Figure 1.1 does not show the top cover from glass that is used for circuit protection. Table 1.1 compares the index contrast $\Delta n/n$ for different waveguide materials.

The refractive index contrast of 60% from SOI waveguides is much higher than in fiberglass (typically 1%) but also substantially higher than in insulator (SiO_2/SiN) or semiconductor heterostructure

(e.g., SiGe/Si) waveguides (typically 10%). This high index contrast allows single-mode waveguides of small dimensions, high curvature of waveguides lines, and high packing density. The SOI waveguide preparation with standard technologies of Si microelectronics guarantees high yield and reproducibility, favors cost-effective fabrication, and offers monolithic integration with electronic supply and readout circuits. The availability of the silicon foundry service [5] gives manifold options for fables activities in design, characterization, and system applications. The silicon waveguide is absorbing in the visible spectral range but gets transparent in the infrared (wavelengths $\lambda > 1.2 \mu\text{m}$). Especially, the telecommunication wavelength regimes around $1.3 \mu\text{m}$ and $1.55 \mu\text{m}$ are compatible with Si photonics [6, 7]. However, the available wavelength regime in low-doped Si is much broader, at least up to $8 \mu\text{m}$. Impurities like oxygen or carbon may disturb the transparency in wavelength bands above $8 \mu\text{m}$ [8].

Figure 1.1 Silicon-on-insulator (SOI) waveguide structure. Upper part: Starting substrate consisting of a Si substrate covered with an oxide layer (buried oxide [BOX]) and a single crystalline Si top layer. After selective etching, a waveguide with a width W and a height H is formed (lower part). Partial etching of the top Si layer down to a thickness h creates a ridge waveguide (left side), and complete etching forms a wire structure. A protective oxide layer (not shown here) covers the waveguide structure.

Table 1.1 Refractive index contrast of typical waveguide structures

Material	n	$\Delta n/n$
Glass fiber	1.5	1%
SiO ₂ /SiN	1.5	10%
Semiconductor heterostructure	3.5	10%
SOI	3.5	60%

Note: Given is the refractive index n of the core material and the relative change $\Delta n/n$ between the core and the cladding. The high index contrast of SOI waveguides allows dense packing of photonic structures.

1.2 Si-Based Photonics

Active devices in photonics for emission, detection, and absorption modulation need strong light-matter interaction in the selected infrared transmission regime. This needs a different material for the active devices that should provide a strong light-matter interaction at the selected wavelength regime but with a good transparency of the Si waveguides.

As favorite solutions for these contrary requests for waveguide and active device emerged heterostructure semiconductor waveguide/device combinations. The semiconductor for the device needs to be chosen with a bandgap E_g lower than that of Si ($E_{gSi} = 1.12$ eV at room temperature). This provides a wavelength regime

$$1.24 \mu\text{m}/E_g (\text{eV}) < \lambda < 1.1 \mu\text{m} \quad (1.1)$$

that fulfils both high transparency of the Si waveguide and strong light-matter interaction for small active devices.

Silicon-Based Photonics as the title of this book refers to the fact that a silicon-based heterostructure is essential to fulfilling all the basic photonic system functions. The heterostructures are chosen either from a group III/V semiconductor on Si or preferably from a group IV semiconductor on Si. In the latter case, “group IV photonics” is an alternative term for this flourishing research topic.

The envisaged application spectrum of Si photonics started with telecommunication [9] networks in metro areas and then expanded to data center and cloud service [10], to on-chip clock

distribution, and to links between cores of multicore processors and links between core and memories. The last-mentioned application spectra address the bottleneck in on-chip communication in ultra-large-scale integrated circuits. Figure 1.2 shows the principally simple arrangement of the optical path on the example of the clock distribution. The laser light couples with the chip from an external laser via a fixed monomode fiberglass mounting. The use of an external laser has the advantages that available high-performance lasers may be used, that power for the laser operation is distributed outside the thermally stressed electronic chip, and that this external clock laser may be used for several chips. The light is modulated either externally or internally, and then it is distributed via waveguides into different subchip areas. In Fig. 1.2, an internal modulator varies the laser light intensity that is distributed to different chip regions by the waveguide lines split up from the input line. Similar schemes provide fast access to memory contents for processor operation. Germanium photodetectors (d) convert the optical signal into an electrical signal at the waveguide line ends. The electrical signal is then distributed around within the small chip regions without the power and speed problems of the electrical clock distribution on large chip areas. Although the scheme is rather simple, the realization on an already complex electronic chip needs to overcome integration process and packaging issues. The majority of system investigations [11] use the common telecom wavelength of 1.3–1.6 μm , but years ago Soref [12] had already backed the use of the broad available wavelength spectrum from near infrared to mid-infrared. This broad spectrum not only delivers an incredible number of frequency slots for communication but also offers new possibilities for imaging and sensing in biology and chemistry [9, 11, 13]. The wavelength regime between 1.5 μm and 3 μm spans a frequency regime from 200 THz to 100 THz, a difference that is a thousand times the frequency span now used or planned for mobile communication or automotive radar. Interference of two lasers with slightly different wavelengths provides a signal the frequency of which may be chosen from the millimeter wavelength to the terahertz range, depending on the frequency difference [14]. Compact chip-sized solutions based on silicon photonics will certainly push the applications in this area between microwave and optics.

Figure 1.2 Scheme of an optical clock frequency distribution. Laser light from an external source is coupled in the chip waveguide via a grating coupler structure (from the right side).

1.3 Book Content

The book focuses on the integration of heterostructure devices with Si photonics, which has resulted in the recent advances of a photonics branch that is named “Si-based photonics.” Some material and device phenomena appear in heterostructures not present in Si stand-alone technology. The most prominent of these phenomena are lattice mismatch, dislocation generation, high elastic strain, and metastable alloys. Strong progress in material science now allows the utilization of the effects from strain and metastability. These effects are also interesting in microelectronics for performance improvements, but in Si-based photonics, they are necessary for full functionality.

The reader will find basics about band structure and optical properties in Chapter 2. A concise treatment of classical Si-photonics topics is given in Chapters 3–7, with explanations of waveguides, resonators, couplers, photonic crystal, and slow light. These chapters are mainly for readers who are interested in the topic because of its increasing importance in different fields. Chapters 8–12 cover different device structures for light emission, detection, modulation, extension of the wavelength beyond $1.6\ \mu\text{m}$, and lasing. An outlook for the next challenges is given in Chapter 13.

With the given mix of basics and front-end research, the authors hope to meet the demands of a broad audience, from students and researchers to engineers who are already working in this field or

who intend to start studies because of the widespread potential in technology and application.

References

1. R. A. Soref and J. P. Lorenzo (1986). All-silicon active and passive guided wave components for $\lambda = 1.3 \mu\text{m}$ and $1.6 \mu\text{m}$, *IEEE J. Quantum Electron.*, **22**, 873–879.
2. A. Splett, J. Schmidtchen, B. Schuppert, K. Petermann, E. Kasper and H. Kibbel (1990). Low loss optical ridge waveguides in a strained GeSi epitaxial layer grown on silicon, *Electron. Lett.*, **26**, 1035.
3. G. Abstreiter (1992). Engineering the future of electronics, *Phys. World*, **5**, 36.
4. E. Kasper, H. J. Mussing and H. G. Grimmeiss (eds.) (2009). *Advances in Electronic Materials* (TransTech Publication, Zurich, Switzerland).
5. L. Chrostowski and M. Hochberg (2015). *Silicon Photonics Design* (Cambridge Univ. Press) ISBN: 978-1-107-08545-9
6. G. T. Read (2008). *Silicon Photonics: The State of the Art* (John Wiley, Hoboken) ISBN: 978-0-470-02579-6.
7. G. T. Read and A. P. Knights (2004). *Silicon Photonics: An Introduction* (John Wiley, Hoboken) ISBN: 978-0-470-87034-7.
8. Focus Issue on Silicon Photonics (2010). *Nat. Photonics*, **4**(8), 491.
9. S. Fathpour and B. Jalali (eds.) (2012). *Silicon Photonics for Telecommunication and Biomedicine* (CRC Press, USA) ISBN: 978-1-4398-0637-1.
10. D. Inniss and R. Rubenstein (2017). *Silicon Photonics: Fueling the Next Information Revolution* (Elsevier, Morgan Kaufmann) ISBN: 978-0-1280-2975-6
11. L. Vivien and L. Pavesi (eds.) (2013). *Handbook of Silicon Photonics* (CRC Press, USA) ISBN: 978-1-4398-3610-1.
12. R. A. Soref, S. J. Emelett and W. R. Buchwald (2006). Silicon waveguided components for the long-wave infrared region, *J. Opt. A: Pure Appl. Opt.*, **8**, 840–848.
13. L. Pavesi and D. Lockwood (eds.) (2016). *Silicon Photonics III-Systems and Applications* (Springer, Germany) Topics in Applied Physics, Vol. 122.
14. Focus Issue on Microwave Photonics (2015). *IEEE Microwave Mag.*, **16**(8), 28–94.

References

1. Landolt-Börnstein (2001). *Group III-Condensed Matter*, Vol. 41, Semiconductors, electronically available at <http://materials.springer.com>.
2. C. F. Klingshirn (2012). *Semiconductor Optics*, 4th Ed. (Springer).
3. D. E. Aspnes and A. A. Studna (1983). *Phys. Rev. B*, **27**, 985.
4. E. Kasper and D. J. Paul (2005). *Silicon Quantum Integrated Circuits* (Springer).
5. J. Humlicek (2000). *Properties of Silicon Germanium and SiGe: Carbon*, *EMIS Datareviews Series*, Vol. 24 (INSPEC, IEE, London), p. 249.
6. M. Oehme, M. Kaschel, J. Werner, O. Kirfel, M. Schmid, B. Bahouchi, E. Kasper and J. Schulze (2010). Germanium on silicon photodetectors with broad spectral range, *J. Electrochem. Soc.*, **157**, 144–148.
7. J. Menendez, M. Noel, J. C. Zwickels and D. Lockwood (2017). Resonant indirect optical absorption in germanium, *Phys. Rev. B*, **96**, 121201.
8. J. Liu (2014). Monolithically integrated Ge-on-Si active photonics, *Photonics*, **1**, 162–197.
9. X. Wang and J. Liu (2018). Emerging technologies in Si active photonics, *J. Semicond.*, **39**, 061001, doi: 10.1088/1674-4926/39/6/061001.

References

1. M. Born and E. Wolf (1999). *Principles of Optics* (Cambridge Univ. Press, Cambridge, UK).
2. W. Bogaerts, D. Taillaert, B. Luyssaert, P. Dumon, J. Van Campenhout, P. Bienstman, D. Van Thourhout, R. Baets, V. Wiaux and S. Beckx (2004).

- Basic structures for photonic integrated circuits in silicon-on-insulator, *Opt. Express*, **12**, 1583–1591.
3. D. Dai, Y. Shi and S. He (2006). Characteristic analysis of nano silicon rectangular waveguides for planar light-wave circuits of high integration, *Appl. Opt.*, **45**, 4941–4946.
 4. S. T. Lim, C. E. Png, E. A. Ong and Y. L. Ang (2007). Single mode, polarization-independent submicron silicon waveguides based on geometrical adjustments, *Opt. Express*, **15**, 11061–11072.
 5. K. Petermann (1976). Properties of optical rib-guides with large cross-section, *Archiv für Elektronik und Übertragungstechnik*, **30**, 139–140.
 6. R. A. Soref, J. Schmidtchen and K. Petermann (1991). Large single-mode rib waveguides in GeSi-Si and Si-on-SiO₂, *IEEE J. Quantum Electron.*, **27**, 1971–1974.
 7. A. G. Richman, G. T. Reed and F. Namavar (1994). Silicon-on-insulator optical rib waveguide loss and mode characteristics, *J. Lightwave Technol.*, **12**, 1771–1776.
 8. J. Schmidtchen, A. Splett, B. Schuppert, K. Petermann and G. Burbach (1991). Low loss singlemode optical waveguides with large cross-section in silicon-on-insulator, *Electron. Lett.*, **27**, 1486.
 9. S. P. Pogossian, L. Vescan and A. Vonsovici (1998). The single-mode condition for semiconductor rib waveguides with large cross section, *J. Lightwave Technol.*, **16**, 1851–1853.
 10. J. Xia and J. Yu (2004). Single-mode condition for silicon rib waveguides with trapezoidal cross-section, *Opt. Commun.*, **230**, 253–257.
 11. J. Lousteau, D. Furniss, A. B. Seddon, T. M. Benson, A. Vukovic and P. Sewell (2004). The single-mode condition for silicon-on-insulator optical rib waveguides with large cross section, *J. Lightwave Technol.*, **22**, 1923–1929.
 12. X. Xu, S. Chen, J. Yu and X. Tu (2009). An investigation of the mode characteristics of SOI submicron rib waveguides using the film mode matching method, *J. Opt. A: Pure Appl. Opt.*, **11**, 015508.
 13. K. K. Lee, D. R. Lim, L. C. Kimerling, J. Shin and F. Cerrina (2001). Fabrication of ultralow-loss Si/SiO₂ waveguides by roughness reduction, *Optics Lett.*, **26**, 1888–1890.
 14. P. Dumon, W. Bogaerts, V. Wiaux, J. Wouters, S. Beckx, J. Van Campenhout, D. Taillaert, B. Luyssaert, P. Bienstman, D. Van Thourhout and R. Baets (2004). Low-loss SOI photonic wires and ring resonators fabricated with deep UV lithography, *IEEE Photonics Technol. Lett.*, **16**, 1328–1330.

15. F. Grillot, L. Vivien, S. Laval, D. Pascal and E. Cassan (2004). Size influence on the propagation loss induced by sidewall roughness in ultrasmall SOI waveguides, *IEEE Photonics Technol. Lett.*, **16**, 1661–1663.
16. A. Sakai, G. Hara and T. Baba (2001). Propagation characteristics of ultrahigh- Δ optical waveguide on silicon-on-insulator substrate, *Jpn. J. Appl. Phys.*, **40**, L383–L385.
17. V. R. Almeida, R. R. Panepucci and M. Lipson (2003). Nanotaper for compact mode conversion, *Opt. Lett.*, **28**, 1302–1304.
18. S. J. McNab, et al. (2003). Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides, *Opt. Express*, **11**, 2927–2939.
19. K. Yamada, et al. (2004). Microphotonics devices based on silicon wire waveguiding system, *IEICE Trans. Electron.*, **E87-C**(3), 351–358.
20. Y. A. Vlasov, et al. (2004). Losses in single-mode silicon-on-insulator strip waveguides and bends, *Opt. Express*, **12**, 1622–1631.
21. D. R. Lim (2000). Device integration for silicon microphotonics platforms, PhD thesis, MIT.
22. T. Tsuchizawa, T. Watanabe, E. Tamechika, T. Shoji, K. Yamada, J. Takahashi, S. Uchiyama, S. Itabashi and H. Morita (2002). Fabrication and evaluation of submicron-square Si wire waveguides with spot-size converters, *Paper TuU2 presented at LEOS Annual Meeting*, Glasgow, UK, p. 287.
23. R. U. Ahmad, F. Pizzuto, G. S. Camarda, R. L. Espinola, H. Rao and R. M. Osgood, Jr. (2002). Ultracompact corner-mirrors and T-branches in silicon-on-insulator, *IEEE Photonics Technol. Lett.*, **14**, 65.
24. P. Dumon, W. Bogaerts, J. Van Campenhout, V. Wiaux, J. Wouters, S. Beckx and R. Baets (2003). Low-loss photonic wires and compact ring resonators in silicon-on-insulator, *LEOS Benelux Annual Symposium 2003*, Netherlands.
25. M. A. Webster, R. M. Pafchek, G. Sukumaran and T. L. Koch (2005). Low-loss quasi-planar ridge waveguides formed on thin silicon-on-insulator, *Appl. Phys. Lett.*, **87**, 231108-1-3.
26. Y. Qian, S. Kim, J. Song, G. P. Nordin and J. Jiang (2006). Compact and low loss silicon-on-insulator rib waveguide 90° bend, *Opt. Express*, **14**, 6020–6028.

References

1. E. A. J. Marcatilli (1969). Bends in optical dielectric waveguides, *Bell Syst. Tech. J.*, **48**, 2103–2132.
2. B. E. Little, S. T. Chu, H. A. Haus, et al. (1997). Microring resonator channel dropping filters, *J. Lightwave Technol.*, **15**(6), 998–1005.
3. A. Yariv (2000). Universal relations for coupling of optical power between microresonators and dielectric waveguides, *Electron. Lett.*, **36**(4), 321–322.
4. L. Caruso and I. Montrosset (2003). Analysis of a racetrack microring resonator with MMI coupler, *J. Lightwave Technol.*, **21**(1), 206–210.
5. J. K. S. Poon, J. Scheuer, S. Mookherjea, et al. (2004). Matrix analysis of microring coupled-resonator optical waveguides, *Opt. Express*, **12**(1), 90–103.
6. S. Darmawan, Y. M. Landobasa and M. K. Chin (2007). Pole-zero dynamics of high-order ring resonator filters, *J. Lightwave Technol.*, **25**(6), 1568–1575.
7. R. Grover, P. P. Absil, T. A. Ibrahim, et al. (2004). III-V semiconductor optical micro-ring resonators, *Microresonators as Building Blocks for VLSI Photonics: International School of Quantum Electronics, AIP Conference Proceedings*, Vol. 709, 110–29 2004
8. Y. Yanagase, S. Suzuki, Y. Kokubun, et al. (2002). Box-like filter response and expansion of FSR by a vertically triple coupled microring resonator filter, *J. Lightwave Technol.*, **20**(8), 1525–1529.

9. J. Heebner, R. Grover and T. Ibrahimli (2007). *Optical Microresonators: Theory, Fabrication, and Applications* (Springer-Verlag, Berlin).
10. Q. Z. Huang, Y. D. Yu and J. Z. Yu (2009). Experimental investigation on submicron rib waveguide microring/racetrack resonators in silicon-on-insulator, *Opt. Commun.*, **282**, 22–26.
11. T. Barwicz, M. R. Watts, M. A. Popovic, et al. (2007). Polarization-transparent microphotonic devices in the strong confinement limit, *Nat. Photonics*, **1**(1), 57–60.
12. X. Yan, C. S. Ma, Y. Z. Xu, et al. (2005). Characteristics of vertical bent coupling between straight and curved rectangular optical waveguides, *Optik*, **116**(8), 397–403.
13. D. Marcuse (1972). *Light Transmission Optics*, 2nd ed. (Van Nostrand Reinhold, New York).
14. V. Subramaniam, G. N. DeBrabander, D. H. Naghski, et al. (1997). Measurement of mode field profiles and bending and transition losses in curved optical channel waveguides, *J. Lightwave Technol.*, **15**(6), 990–997.
15. K. K. Lee, D. R. Lim, H. C. Luan, et al. (2000). Effect of size and roughness on light transmission in a Si/SiO₂ waveguide: experiments and model, *Appl. Phys. Lett.*, **77**(11), 1617–1619.
16. P. K. Tien (1971). Light waves in thin films and integrated optics, *Appl. Opt.*, **10**(11), 2395.
17. S. M. Zheng, H. Chen and A. W. Poon (2006). Microring-resonator cross-connect filters-in silicon nitride: rib waveguide dimensions dependence, *J. Sel. Topics Quantum Electron.*, **12**(6), 1380–1387.
18. P. Dumon, W. Bogaerts, V. Wiaux, et al. (2004). Low-loss SOI photonic wires and ring resonators fabricated with deep UV lithography, *IEEE Photonics Technol. Lett.*, **16**(5), 1328–1330.
19. F. N. Xia, L. Sekaric and Y. Vlasov (2007). Ultracompact optical buffers on a silicon chip, *Nat. Photonics*, **1**(1), 65–71.
20. Q. F. Xu, B. Schmidt, S. Pradhan, et al. (2005). Micrometre-scale silicon electro-optic modulator, *Nature*, **435**(7040), 325–327.
21. S. J. Xiao, M. H. Khan, H. Shen, et al. (2007). Compact silicon microring resonators with ultra-low propagation loss in the C band, *Opt. Express*, **15**, 14467–14475.
22. U. Plachetka, N. Koo, T. Wahlbrink, et al. (2008). Fabrication of photonic ring resonator device in silicon waveguide technology using soft UV-nanoimprint lithography, *IEEE Photonics Technol. Lett.*, **20**(5–8), 490–492.

23. Q. Z. Huang, J. Z. Yu, S. W. Chen, et al. (2008). Design, fabrication and characterization of a high-performance microring resonator in silicon-on-insulator, *Chinese Phys. B*, **17**(7), 2562–2566.
24. F. N. Xia, L. Sekaric and Y. A. Vlasov (2006). Mode conversion losses in silicon-on-insulator photonic wire based racetrack resonators, *Opt. Express*, **14**(9), 3872–3886.
25. Q. Z. Huang, Y. D. Yu and J. Z. Yu (2009). Design and realization of a microracetrack resonator based polarization splitter in silicon-on-insulator, *J. Opt. A: Pure Appl. Opt.*, **11**, 015506.
26. F. N. Xia, M. Rooks, L. Sekaric, et al. (2007). Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects, *Opt. Express*, **15**, 11934–11941.
27. S. Xiao, M. H. Khan, H. Shen, et al. (2007). Multiple-channel silicon micro-resonator based filters for WDM applications, *Opt. Express*, **15**(12), 7489–7498.
28. Q. F. Xu, S. Manipatruni, B. Schmidt, et al. (2007). 12.5 Gbit/s carrier-injection-based silicon micro-ring silicon modulators, *Opt. Express*, **15**(2), 430–436.
29. Y. Vlasov, W. M. J. Green and F. Xia (2008). High-throughput silicon nanophotonic wavelength-insensitive switch for on-chip optical networks, *Nat. Photonics*, **2**(4), 242–246.
30. O. Lin, O. J. Painter and G. P. Agarwal (2007). Nonlinear optical phenomena in silicon waveguides: modeling and applications, *Opt. Express*, **15**, 16606.
31. L. Zhang, A. M. Agarwal, L. C. Kimerling and J. Michel (2014). Nonlinear group IV photonics based on silicon and germanium: from near-infrared to mid-infrared, *Nanophotonics*, **3**, 247–268.
32. H. K. Tsang and Y. Liu (2008). Nonlinear optical properties of silicon waveguides, *Semicond. Sci. Technol.*, **23**(6), 064007.
33. J. Kerr (1875). A new relation between electricity and light: Dielectric media birefringent, *Phil. Mag.*, **50**(332), 337–348.
34. J. Leuthold, C. Koos and W. Freude (2010). Nonlinear silicon photonics, *Nat. Photon.*, **4**, 535–544.
35. M. Dinu, F. Quochi and H. Garcia (2003). Third-order nonlinearities in silicon at telecom wavelengths, *Appl. Phys. Lett.*, **82**, 2954–2956.
36. C. Lacava, M. A. Ettabib and P. Petropoulos (2017). Nonlinear silicon photonic signal processing devices for future optical networks, *Appl. Sci.*, **7**, 103.

37. X. Xu et. al. (2017). Observation of third-order nonlinearities in graphene oxide film at telecommunication wavelength, *Sci. Rep.*, **7**, 9646.
38. H. S. Rong, S. B. Xu, Y. H. Kuo, et al. (2007). Low-threshold continuous-wave Raman silicon laser, *Nat. Photonics*, **1**(4), 232–237.
39. T. A. Ibrahim, K. Amarnath, L. C. Kuo, et al. (2004). Photonic logic NOR gate based on two symmetric microring resonators, *Opt. Lett.*, **29**(23), 2779–2781.
40. T. A. Ibrahim, R. Grover, L. C. Kuo, et al. (2003). All-optical AND/NAND logic gates using semiconductor microresonators, *IEEE Photonics Technol. Lett.*, **15**(10), 1422–1424.
41. Q. F. Xu, J. Shakya and M. Lipson (2006). Direct measurement of tunable optical delays on chip analogue to electromagnetically induced transparency, *Opt. Express*, **14**(14), 6463–6468.
42. J. Thomson, F. Y. Gardens, J.-M. Fédéli, S. Zlatanovic, Y. Hu, B. P. P. Kuo, E. Myslivets, N. Alic, S. Radic, G. Z. Mashanovich and G. Reed (2012). 50-Gb/s silicon optical modulator, *IEEE Photon. Technol. Lett.*, **24**(4), 234–236.
43. M. Calvo et. al. (2019). Ring resonator designed for biosensing applications manufactured on 300 mm SOI in an industrial environment, *Jpn. J. Appl. Phys.*, **58**, SBBE02.

References

1. R. A. Soref and J. P. Lorenzo (1986). All silicon active and passive guided-wave components for $\lambda = 1.3 \mu\text{m}$ and $1.6 \mu\text{m}$, *IEEE J. Quantum Electron.*, **22**, 873–879.
2. Y. A. Vlasov and S. J. McNab (2004). Losses in single-mode silicon-on-insulator strip waveguide and bends, *Opt. Express*, **12**, 1622–1631.
3. L. Vivien, S. Laval, B. Dumont, S. Lardenois, A. Koster and E. Cassan (2002). Polarization-independent single-mode rib waveguides on silicon-on-insulator for telecommunication wavelengths, *Opt. Commun.*, **210**(1), 43–49.
4. S. J. McNab, N. Moll and Y. A. Vlasov (2003). Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides, *Opt. Express*, **11**, 2927–2939.
5. D. Taillaert, P. Bienstman and R. Baets (2004). Compact efficient broadband grating coupler for silicon-on-insulator waveguides, *Opt. Lett.*, **29**, 2749–2751.
6. I. Day, I. Evans, A. Knights, F. Hopper, et al. (2003). Tapered silicon waveguides for low insertion loss highly-efficient high-speed electronic variable optical attenuators, *Optical Fiber Communications Conference*, 249–251.
7. Y. Li, J. Yu and S. Chen (2005). Rearrangeable nonblocking SOI waveguide thermo-optic 4×4 switch matrix with low insertion loss and fast response, *IEEE Photonics Technol. Lett.*, **17**, 1641–1643.
8. A. Sure, T. Dillon, J. Murakowski, C. Lin, D. Pustai and D. W. Prather (2003). Fabrication and characterization of three-dimensional silicon tapers. *Opt. Express*, **11**, 3555–3561.

9. T. Brenner, W. Hunziker, M. Smit, M. Bachmann, G. Guekos and H. Melchior (1992). Vertical InP/InGaAsP tapers for low-loss optical fiber-waveguide coupling, *Electron. Lett.*, **28**, 2040–2041.
10. M. Chien, U. Koren, T. L. Koch, B. I. Miller, M. G. Young, M. Chien and G. Raybon (1991). Short cavity distributed Bragg reflector laser with an integrated tapered output waveguide, *IEEE Photonics Technol. Lett.*, **3**, 418–420.
11. T. Brenner and H. Melchior (1993). Integrated optical modeshape adapters in InGaAsP/InP for efficient fiber-to-waveguide coupling, *IEEE Photonics Technol. Lett.*, **5**, 1053–1056.
12. G. Muller, G. Wender, L. Stoll, H. Westermeier and D. Seeberger (1993). Fabrication techniques for vertically tapered InP/InGaAsP spot-size transformers with very low loss, *Proc. Eur. Conf. Integrated Optics*, Neuchatel, Switzerland.
13. B. Jacobs, R. Zengerle, K. Faltin and W. Weiershausen (1995). Vertically tapered spot size transformers by a simple masking technique, *Electron. Lett.*, **31**, 794–796.
14. L. Pavesi and D. J. Lockwood (2004). *Silicon Photonics* (Springer, Berlin).
15. www.confluentphotonics.com/technology/technical_papers.php#fabrication
16. J. J. Fijol, E. E. Fike, P. B. Keating, D. Gilbody, J. LeBlanc, S. A. Jacobson, W. J. Kessler and M. B. Frish (2003). Fabrication of silicon-on-insulator adiabatic tapers for low loss optical interconnection of photonic devices, *Proc. SPIE*, **4997**, Photonics Packaging and Integration III, <https://doi.org/10.1117/12.479371>.
17. V. R. Almeida, R. R. Panepucci and M. Lipson (2003). Nanotaper for compact mode conversion, *Opt. Lett.*, **28**, 1302–1304.
18. T. Shoji, T. Tsuchizawa, T. Watanabe, K. Yamada and H. Morita (2002). Low loss mode size converter from 0.3 μm square Si waveguides to singlemode fibres, *Electron. Lett.*, **38**, 1669–1700.
19. S. J. McNab, N. Moll and Y. A. Vlasov (2003). Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides, *Opt. Express*, **11**, 2927–2939.
20. Y. Liu and J. Yu (2007). Low-loss coupler between fiber and waveguide based on silicon-on-insulator slot waveguides, *Appl. Opt.*, **46**, 7858–7861.
21. S. H. Tao, J. Song, Q. Fang, M. Yu, G. Lo and D. Kwong (2008). Improving coupling efficiency of fiber-waveguide coupling with a double-tip coupler, *Opt. Express*, **16**, 20803–20808.

22. Z. Lu and D. W. Prather (2004). Total internal reflection–evanescent coupler for fiber-to-waveguide integration of planar optoelectronic devices, *Opt. Lett.*, **29**, 1784–1750.
23. S. Janz, B. Lamontagne, A. Delage, A. Bogdanov, D. X. Xu and K. P. Xu (2005). Single layer a-Si GRIN waveguide coupler with lithographically defined facets, *IEEE International Conference on Group IV Photonics*, 129–131.
24. D. Taillaert, W. Bogaerts, P. Bienstman, T. Krauss, P. Van. Daele, I. Moerman, S. Verstuyft, K. De Mesel and R. Baets (2002). An out-of-plane grating coupler for efficient butt-coupling between compact planar waveguides and single-mode fibers, *IEEE J. Quantum Electron.*, **38**, 949–995.
25. D. Taillaert, R. Baets, P. Dumon, W. Bogaerts, D. Van Thourhout, B. Luyssaert, V. Wiaux, S. Beckx and J. Wouters (2005). Silicon-on-insulator platform for integrated wavelength-selective components, *Proc. IEEE/LEOS Workshop Fibres and Optical Passive Components*, Italy, 115–120.
26. F. Laere, G. Roelkens, M. Ayre, J. Schrauwen, D. Taillaert and R. Baets (2007). Compact and highly efficient grating couplers between optical fiber and nanophotonic waveguide, *J. Lightwave Technol.*, **12**, 151–156.
27. G. Roelkens, D. Thourhout and R. Baets (2006). High efficiency Silicon-on-Insulator grating coupler based on a poly-silicon overlay, *Opt. Express*, **12**, 11622–11630.
28. G. Roelkens, D. Thourhout and R. Baets (2008). High efficiency diffraction grating coupler for interfacing a single mode optical fiber with a nanophotonic silicon-on-insulator waveguide circuit, *Appl. Phys. Lett.*, **92**, 131101–131103.
29. G. Roelkens, D. Thourhout and R. Baets (2007). High efficiency grating coupler between silicon-on-insulator waveguides and perfectly vertical optical fibers, *Opt. Lett.*, **32**, 1495–1497.
30. J. Schrauwen, F. Laere, D. Thourhout and R. Baets (2007). Focused-ion-beam fabrication of slanted grating couplers in silicon-on-insulator waveguide, *IEEE Photonics Technol. Lett.*, **19**, 816–818.
31. T. Ang, G. Reed, A. Vonsovici, A. Evans, P. Routly and M. Josey (2000). Effects of grating heights on highly efficient unbond SOI waveguide grating couplers, *IEEE Photonics Technol. Lett.*, **12**, 59–61.
32. J. K. Butler, N. H. Sun, G. A. Evans, L. Pang and P. Congdon (1998). Grating-assisted coupling of light between semiconductor and glass waveguides, *IEEE J. Lightwave Technol.*, **16**(6), 1038–1048.

33. R. Orobttchouk, N. Schnell, T. Benyattou, J. Gregoire, S. Lardenois, M. Heitzmann and J. M. Fedeli (2003). New ARROW optical coupler for optical interconnect, *IEEE International Conference on Interconnect Technology*, USA, 233–235.
34. G. Z. Masanovic, V. M. N. Passaro and G. T. Reed (2003). Dual grating-assisted directional coupling between fibres and thin semiconductor waveguides, *IEEE Photonics Technol. Lett.*, **15**, 1395–1397.
35. Y. Fu, T. Ye, W. Tang and T. Chu (2014). Efficient adiabatic silicon-on-insulator waveguide taper, *Photon. Res.*, **2**, A41–A44.
36. K. K. Lee, D. R. Lim, D. Pan, C. Hoepfner, W. Oh, K. Wada, L. C. Kimerling, K. P. Yap and M. T. Doan (2005). Mode transformer for miniaturized optical circuits, *Opt. Lett.*, **30**, 498–500.
37. M. Galarza, D. Van Thourhout, R. Baets and M. Lopez-Amo (2008). Compact and highly-efficient polarization independent vertical resonant couplers for active-passive monolithic integration, *Opt. Express*, **16**, 8350–8358.
38. T. Tsuchizawa, K. Yamada, T. Watanabe, H. Fukuda, H. Nishi, H. Shinojima and S. Itabashi (2008). SSCs for rib-type silicon photonic wire waveguides, *Proc. IEEE Intern. Conf. Group IV Photonics*, Tokyo, 200–202.
39. W. Sfar Zaoui, A. Kunze, W. Vogel, M. Berroth, J. Butschke, F. Letzkus and J. Burghartz (2014). Bridging the gap between optical fibers and silicon photonic integrated circuits, *Opt. Express*, **22**, 1277–1286.

References

1. E. Yablonnovitch (1987). Inhibited spontaneous emission in solid-state physics and electronics, *Phys. Rev. Lett.*, **58**(20), 2059–2062.
2. S. John (1987). Strong localization of photons in certain disordered dielectric superlattices, *Phys. Rev. Lett.*, **58**(23), 2486–2489.
3. K. Sakoda (2001). *Optical Properties of Photonic Crystals* (Springer-Verlag, Berlin).
4. J. D. Joannapolous, R. D. Meade and J. N. Winn (1995). *Photonic Crystal-Molding the Flow of Light* (Princeton University Press).
5. K. S. Yee (1966). Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media, *IEEE Trans. Antennas Propagat.*, **AP-14**, 302.
6. A. Tavlove (1995). *Computational Electrodynamics: The Finite-Difference Time-Domain Method* (Artech House, Norwood).
7. H. Yu, J. Yu, F. Sun, Z. Li and S. Chen (2007). Systematic considerations for the patterning of photonic crystal devices by electron beam lithography, *Opt. Commun.*, **271**(3), 241–247.
8. J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith and E. P. Ippen (2003). Photonic-bandgap microcavities in optical waveguides, *Nature*, **425**, 944–947.

9. Y. Akahane, T. Asano, B. S. Song and S. Noda (1997). High-Q photonic crystal nanocavity in a two-dimensional photonic crystal, *Nature*, **390**, 143–145.
10. Y. Akahane, T. Asano, B.-S. Song and S. Noda (2005). Fine-tuned high-Q photonic-crystal nanocavity, *Opt. Express*, **13**(4), 1202–1214.
11. T. Asano, B. S. Song and S. Noda (2006). Analysis of the experimental Q factors (~1 million) of photonic crystal nanocavities, *Opt. Express*, **14**(5), 1996–2002.
12. T. Yasushi, H. Hiroyuki, T. Yoshinori, S. Bong-Shik, A. Takashi and S. Noda (2007). High-Q nanocavity with a 2-ns photon lifetime, *Opt. Express*, **15**(25), 17206–17213.
13. H. Yu, J. Yu, Y. Yu and S. Chen (2009). Design and fabrication of a photonic crystal channel drop filter based on an asymmetric Silicon-on-insulator slab, *J. Nanosci. Nanotechnol.*, **9**, 974–977.

References

1. H. Lorentz (1880). Relation between propagation of light and density of matter; *Wied. Ann. Phys. Chem.*, **9**(4), 641–665.

2. J. R. Pierce (1950). Traveling-wave tubes, *Bell Syst. Tech. J.*, **29**(4), 608–671.
3. L. Field (1949). Some slow-wave structures for traveling-wave tubes, *Proc. IRE*, **37**(1), 34–40.
4. R. W. Boyd (2005). Applications of slow-light in telecommunications and optical switching, Presented at Photonics West.
5. E. Parra and J. Lowell (2007). Toward applications of slow light technology, *Optics and Photonics News*, **18**(11), 40–45.
6. M. Fisher and S. Chuang (2005). Variable group delay and pulse reshaping of high bandwidth optical signals, *IEEE J. Quantum Electron.*, **41**(6), 885–894.
7. M. Fleischhauer and M. Lukin (2002). Quantum memory for photons: dark-state polaritons, *Phys. Rev. A*, **65**(2), 22314.
8. S. Harris and L. Hau (1999). Nonlinear optics at low light levels, *Phys. Rev. Lett.*, **82**(23), 4611–4614.
9. W. Jemison, T. Yost and P. Herczfeld (1996). Acoustooptically controlled true time delays: experimental results, *IEEE Microwave Guided Wave Lett.*, **6**(8).
10. Z. Liu, et al. (2006). X-band continuously variable true-time delay lines using air-guiding photonic bandgap fibers and a broadband light source, *Opt. Lett.*, **31**(18), 2789–2794.
11. F. Zimmer and M. Fleischhauer (2004). Sagnac interferometry based on ultraslow polaritons in cold atomic vapors, *Phys. Rev. Lett.*, **92**(25), 253204.
12. Z. Shi, et al. (2007). Slow-light Fourier transform interferometer, *Phys. Rev. Lett.*, **99**(24), 240804.
13. G. Purves, C. Adams and I. Hughes (2006). Sagnac interferometry in a slow-light medium, *Phys. Rev. A*, **74**(2), 23805.
14. G. Jundt, et al. (2003). Non-linear Sagnac interferometry for pump-probe dispersion spectroscopy, *Eur. Phys. J. D*, **27**(3), 273–276.
15. C. Garrett and D. McCumber (1970). Propagation of a Gaussian light pulse through an anomalous dispersion medium, *Phys. Rev. A*, **1**(2), 305–313.
16. G. Lenz, B. J. Eggleton, C. K. Madsen and R. E. Slusher (2001). Optical delay lines based on optical filters. *IEEE J. Quantum Electron.*, **37**, 525–532.
17. C. Madsen and J. Zhao (1999). *Optical Filter Design and Analysis: A Signal Processing Approach* (John Wiley & Sons, Inc. New York, NY, USA).

18. C. Madsen (2000). General IIR optical filter design for WDM applications using all-pass filters, *J. Lightwave Technol.*, **18**(6), 860.
19. Q. Xu, et al. (2007). 12.5 Gbit/s carrier-injection-based silicon microring silicon modulators, *Opt. Express*, **15**(2), 430–436.
20. S. Emelett and R. Soref (2005). Design and simulation of silicon microring optical routing switches, *J. Lightwave Technol.*, **23**(4), 1800.
21. V. Van, et al. (2002). Optical signal processing using nonlinear semiconductor microring resonators, *IEEE J. Sel. Top. Quantum Electron.*, **8**(3), 705–713.
22. B. Liu, A. Shakouri and J. Bowers (2004). Passive microring-resonator-coupled lasers, *Appl. Phys. Lett.*, **79**, 3564.
23. Z. Bian, B. Liu and A. Shakouri (2003). InP-based passive ring-resonator-coupled lasers, *IEEE J. Quantum Electron.*, **39**(7), 859–865.
24. A. Yalcin, et al. (2006). Optical sensing of biomolecules using microring resonators. *IEEE J. Sel. Top. Quantum Electron.*, **12**(1), 148–155.
25. A. Yariv, et al. (1999). Coupled-resonator optical waveguide: a proposal and analysis, *Opt. Lett.*, **24**(11), 711–713.
26. J. Heebner and R. Boyd (2002). Slow' and fast 'light in resonator-coupled waveguides, *J. Mod. Opt.*, **49**(14/15), 2629–2636.
27. J. Heebner, R. Boyd and Q. Park (2002). SCISSOR solitons and other novel propagation effects in microresonator-modified waveguides, *J. Opt. Soc. Am. B*, **19**, 722–734.
28. J. Heebner (2003). Nonlinear optical whispering gallery microresonators for photonics, PhD thesis, University of Rochester.
29. J. Poon et al. (2004). Matrix analysis of microring coupled-resonator optical waveguides, *Opt. Express*, **12**(1), 90–103.
30. J. Poon and A. Yariv (2007). Active coupled-resonator optical waveguides. I. Gain enhancement and noise, *J. Opt. Soc. Am. B*, **24**(9), 2378–2388.
31. J. Poon, et al. (2004). Designing coupled-resonator optical waveguide delay lines, *J. Opt. Soc. Am. B*, **21**(9), 1665–1673.
32. J. Khurgin (2008). *Slow Light: Science and Applications* (CRC Press).
33. F. Xia, L. Sekaric and Y. Vlasov (2007). Ultracompact optical buffers on a silicon chip, *Nat. Photonics*, **1**(1), 65–74.
34. J. Cardenas, et al. (2009). Large bandwidth continuously tunable delay using silicon microring resonators, in *Group IV Photonics 2009*.
35. Y. Vlasov, et al. (2005). Active control of slow light on a chip with photonic crystal waveguides, *Nature*, **438**(7064), 65–69.

36. T. Krauss (2007). Slow light in photonic crystal waveguides, *J. Phys. D: Appl. Phys.*, **40**, 2666–2670.
37. S. Zhu, et al. (2000). Time delay of light propagation through defect modes of one-dimensional photonic band-gap structures, *Opt. Commun.*, **174**(1–4), 139–144.
38. H. Gersen, et al. (2005). Real-space observation of ultraslow light in photonic crystal waveguides, *Phys. Rev. Lett.*, **94**(7), 73903.
39. T. Kawasaki, D. Mori and T. Baba (2007). Experimental observation of slow light in photonic crystal coupled waveguides, *Opt. Express*, **15**(16), 10274–10284.
40. M. Soljačić, et al. (2002). Photonic-crystal slow-light enhancement of nonlinear phase sensitivity, *J. Opt. Soc. Am. B*, **19**(9), 2052–2059.
41. B. Corcoran, et al. (2009). Optical performance monitoring via slow light enhanced third harmonic generation in silicon photonic crystal waveguides, *Conference on Optical Fiber Communication*, San Diego, CA, USA.
42. Y. Hamachi, S. Kubo and T. Baba (2009). Slow light with low dispersion and nonlinear enhancement in a lattice-shifted photonic crystal waveguide, *Opt. Lett.*, **34**(7), 1072–1074.
43. K. Inoue, et al. (2009). Enhanced third-order nonlinear effects in slow-light photonic-crystal slab waveguides of line-defect, *Opt. Express*, **17**(9), 7206–7216.
44. S. Ha, et al. (2008). Dispersionless tunneling of slow light in antisymmetric photonic crystal couplers, *Opt. Express*, **16**(2), 1104–1114.
45. T. Baba, et al. (2009). Dispersion-controlled slow light in photonic crystal waveguides, *Proc. Jpn. Acad. Ser. B: Phys. Biol. Sci.*, **85**(10), 443–453.
46. M. Ebnali-Heidari, et al. (2009). Dispersion engineering of slow light photonic crystal waveguides using microfluidic infiltration, *Opt. Express*, **17**(3), 1628–1635.
47. M. Notomi, E. Kuramochi and T. Tanabe (2008). Large-scale arrays of ultrahigh-Q coupled nanocavities, *Nat. Photonics*, **2**(12), 741–747.
48. M. Svaluto Moreolo, V. Morra and G. Cincotti (2008). Design of photonic crystal delay lines based on enhanced coupled-cavity waveguides, *J. Opt. A: Pure Appl. Opt.*, **10**, 064002.
49. B. Corcoran, et al. (2009). Green light emission in silicon through slow-light enhanced third-harmonic generation in photonic-crystal waveguides, *Nat. Photonics*, **3**(4), 206–210.

50. A. Melloni, F. Morichetti and T. Krauss (2009). Slow light in coupled ring resonators and PhC: a comparison, *Advances in Optical Sciences Congress*, OSA Technical Digest (CD) (Optical Society of America, 2009), paper STuC3.
51. S. Serna, P. Colman, W. Zhang, X. Le Roux, C. Caer, L. Vivien and E. Cassan (2016). Experimental GVD engineering in slow light slot photonic waveguides, *Sci. Rep.*, **6**, 26956.
52. J. Leuthold, C. Koos and W. Freude (2010). Nonlinear silicon photonics, *Nat. Photonics*, **4**, 535–544.
53. L. Vivien and L. Pavesi (2013). *Handbook of Silicon Photonics* (CRC Press).

References

1. V. Higgs, E. C. Lightowers, G. Davies, F. Schäffler and E. Kasper (1989). Photoluminescence from MBE Si grown at low temperatures; Donor bound excitons and decorated dislocations, *Semicond. Sci. Technol.*, **4**, 593–598.
2. J. M. Sun, W. Skorupa, T. Dekorsy, M. Helm and L. Rebohle (2004). Efficient ultraviolet electroluminescence from a Gd-implanted silicon metal–oxide–semiconductor device, *Appl. Phys. Lett.*, **85**, 3387.
3. M. Morschbach, M. Oehme and E. Kasper (2007). Visible light emission by a reverse-biased integrated silicon diode, *IEEE Trans. Electron Devices*, **54**, 1091–1094.
4. E. Kasper and M. Morschbach (2013). Method for self-monitoring of breakdown in semiconductor components and semiconductor component constructed thereof, United States Patent US 8,519,732 B2.
5. L. Esaki and R. Tsu (1970). Superlattice and negative differential conductivity in semiconductors, *IBM J. Res. Dev.*, **14**, 61.
6. U. Gnatzmann and K. Clausecker (1974). Theory of direct optical transitions in an optical indirect semiconductor with a superlattice structure, *Appl. Phys.*, **3**, 9.
7. E. Kasper, H. Herzog and H. Kibbel (1975). A one-dimensional SiGe superlattice grown by UHV epitaxy, *Appl. Phys.*, **8**, 199–205.
8. H. Brugger, G. Abstreiter, H. Jorke, H. Herzog and E. Kasper (1986). Folded acoustic phonons in Si/SixGe1-x superlattices, *Phys. Rev.*, **B33**, 5928–5930.
9. R. Zachai, K. Eberl, G. Abstreiter, E. Kasper and H. Kibbel (1990). Photoluminescence in short-period Si/Ge strained layer superlattices, *Phys. Rev. Lett.*, **64**, 1055–1058.
10. G. Theodorou and E. Kasper (2007). Optical properties of Si/Ge superlattices, in *Landolt-Boernstein, New Series*, Vol. III, 34C3, E. Kasper and C. Klingshirn, eds. (Springer Verlag), pp. 50–86.
11. N. Usami and Y. Shiraki (2007). Single and coupled quantum wells: SiGe, in *Landolt-Boernstein, New Series*, Vol. III, 34C3 E. Kasper and C. Klingshirn, eds. (Springer Verlag), pp. 26–49.

12. T. Arguirov, M. Kittler, M. Oehme, N. V. Abrosimov, O. F. Vyvenko, E. Kasper and J. Schulze (2014). Luminescence from germanium and germanium on silicon, *Solid State Phenom.*, **205–206**, 383–393.
13. E. Kasper, M. Oehme, T. Arguirov, J. Werner, M. Kittler and J. Schulze (2012). Room temperature direct band gap emission from Ge p-i-n heterojunction photodiodes, *Adv. OptoElectron.*, **2012**, 916275.
14. R. Koerner, M. Oehme, M. Gollhofer, M. Schmid, K. Kostecki, S. Bechler, D. Widmann, E. Kasper and J. Schulze (2015). Electrically pumped lasing from Ge Fabry-Perot resonators on Si, *Opt. Express*, **23**, 14815–14822.
15. R. Koerner, M. Oehme, M. Gollhofer, M. Schmid, K. Kostecki, S. Bechler, D. Widmann, E. Kasper and J. Schulze (2015). Electrically pumped lasing from Ge Fabry-Perot resonators on Si, *Opt. Express*, **23**, 14815–14822.
16. A. Palmieri, M. Vallone, M. Calciati, A. Tibaldi, F. Bertazzi, G. Ghione and M. Goano (2018). Heterostructure modeling considerations for Ge-on-Si waveguide photodetectors, *Opt. Quantum Electron.*, **50**, 71.
17. M. Oehme, E. Kasper and J. Schulze (2013). GeSn heterojunction diode: detector and emitter in one device, *ECS J. Solid State Sci. Technol.*, **2**(4), 76–78.
18. M. Oehme, M. Gollhofer, D. Widmann, M. Schmid, M. Kaschel, E. Kasper and J. Schulze (2013). Direct bandgap narrowing in Ge LED's on Si substrates, *Opt. Express*, **21**(2), 2206–2211.
19. J. Michel, J. Liu and L. C. Kimerling (2010). High-performance Ge-on-Si photodetectors, *Nat. Photonics*, **4**, 527–533.
20. E. Kasper, M. Kittler, M. Oehme and T. Arguirov (2013). Germanium tin: silicon photonics toward the mid-infrared, *Photonics Res.*, **1**(2), 69–76.
21. E. Kasper (2016). Group IV heteroepitaxy on silicon for photonics, *J. Mater. Res.*, **31**, 3639–3648.
22. T. S. Perova, E. Kasper, M. Oehme, S. Cherevko and J. Schulze (2017). Features of polarized Raman spectra for homogeneous and non-homogeneous compressively strained GeSn alloys, *J. Raman Spectrosc.*, **48**, 993–1001.
23. L. Kormos, M. Kratzer, K. Kostecki, M. Oehme, T. Sikola, E. Kasper, J. Schulze and C. Teichert (2017). Surface analysis of epitaxially grown GeSn alloys with Sn contents between 15% and 18%, *Surf. Interface Anal.*, **49**, 297–302.
24. B. Schwartz, P. Saring, T. Arguirov, M. Oehme, E. Kasper, J. Schulze and M. Kittler (2016). Analysis of EL emitted by LEDs on Si substrates

- containing GeSn/Ge multi quantum wells as active layers, *Solid State Phenom.*, **242**, 361–367.
25. N. von den Driesch, et al. (2018). Advanced GeSn/SiGeSn group IV heterostructure lasers, *Adv. Sci.*, **5**, 1700955.
 26. V. A. Timofeev, A. I. Nikiforov, A. R. Tuktamyshev, V. I. Mashanov, I. D. Loshkarev, A. A. Bloshkin and A. K. Gutakovskii (2018). Pseudomorphic GeSiSn, SiSn and Ge layers in strained heterostructures, *Nanotechnology*, **29**, 154002.
 27. W. Dou, M. Benamara, A. Mosleh, J. Margetis, P. Grant, Y. Zhou, S. Al-Kabi, W. Du, J. Tolle, B. Li, M. Mortazavi and S.-Q. Yu (2018). Investigation of GeSn strain relaxation and spontaneous composition gradient for low - defect and high-Sn alloy growth, *Sci. Rep.*, **8**, 5640.

References

1. E. Kasper (2010). Prospects and challenges of silicon/germanium on-chip optoelectronics, *Front. Optoelectron. China*, **3**, 143–152.
2. C. Penn, T. Fromherz and G. Bauer (2000). Energy gaps and band structure of SiGe and their temperature dependence, EMIS Data Review, Vol. 24 (INSPEC, IEE, England), pp. 125–134.
3. J. Humlicek (2000). Optical functions of the relaxed SiGe alloy, EMIS Data review, Vol. 24 (INSPEC, IEE, England), pp. 249–259.
4. S. M. Sze (1981). *Physics of Semiconductor Devices*, 2nd ed. (John Wiley).
5. S. M. Sze and K. K. Ng (2007). *Physics of Semiconductor Devices*, 3rd ed. (Wiley-Interscience).
6. C. H. Lin and C. W. Liu (2010). Metal-insulator-semiconductor photodetectors, *Sensors*, **10**, 8797–8826.
7. J. Michel, J. Liu and L. C. Kimerling (2010). High performance Ge-on-Si photodetectors, *Nat. Photonics*, **4**, 527–534.
8. D. Bougeard, K. Brunner and G. Abstreiter (2003). Intraband photoresponse of SiGe quantum dot/quantum well multilayers, *Physica E*, **16**, 609–613.

9. R. P. G. Karunasiri, J. S. Park and K. L. Wang (1992). Normal incidence infrared detector using intervalence-subband transitions in SiGe/Si quantum wells, *Appl. Phys. Lett.*, **91**, 2234–2236.
10. K. L. Wang, D. Cha, J. Liu and C. Chen (2007). Ge/Si self-assembled quantum dots and their optoelectronic device applications, *Proc. IEEE*, **95**, 1866–1883.
11. M. A. Gadir, P. Harrison and R. A. Soref (2001). Arguments for p-type quantum-well SiGe/Si photodetectors for the far and very-far (terahertz)-infrared, *Superlatt. Microstruct.*, **30**, 135–143.
12. W. S. Ho, C. H. Lin, T. H. Cheng, W. W. Hsu, Y. Y. Chen, P. S. Kuo and C. W. Liu (2009). Narrow-band metal-oxide-semiconductor photodetector, *Appl. Phys. Lett.*, **94**, 061114-1–061114-3.
13. M. Jutzi, M. Berroth, G. Wöhl, M. Oehme and E. Kasper (2005). Ge-on-Si vertical incidence photodiodes with 39-GHz bandwidth, *IEEE Photonics Technol. Lett.*, **17**, 1510–1512.
14. M. Oehme, J. Werner, E. Kasper, M. Jutzi and M. Berroth (2006). High bandwidth Ge p-i-n photodetector integrated on Si, *Appl. Phys. Lett.*, **89**, 071117.
15. E. Kasper and W. Zhang (2015). Device operation as crystal quality probe, in *Silicon, Germanium and their Alloys: Growth, Defects, Impurities and Nanocrystals*, G. Kissinger and S. Pizzini, eds. (Taylor and Francis, Boca Raton), pp. 341–364.
16. M. Oehme, M. Kaschel, J. Werner, O. Kirfel, M. Schmid, B. Bahouchi, E. Kasper and J. Schulze (2010). Germanium on silicon photodetectors with broad spectral range, *J. Electrochem. Soc.*, **157**, H144–H148.
17. G. H. Rieke (1994). *Detection of Light: From the Ultraviolet to the Submillimeter* (Cambridge Univ. Press).
18. C. H. Lin, C. Y. Yu, C. Y. Peng, W. S. Ho and C. W. Liu (2007). Broadband SiGe/Si quantum dot infrared photodetectors, *J. Appl. Phys.*, **101**, 033117-1–033117-4.
19. M. Oehme, J. Werner, O. Kirfel and E. Kasper (2008). MBE growth of SiGe with high Ge content for optical applications, *Appl. Surf. Sci.*, **254**, 6238–6241.
20. M. Kaschel, M. Oehme, O. Kirfel and E. Kasper (2009). Spectral responsivity of fast Ge photodetectors on SOI, *Solid-State Electron.*, **53**, 909–911.
21. M. Oehme, J. Werner, E. Kasper, S. Klinger and M. Berroth (2007). Photocurrent analysis of a fast Ge p-i-n detector on Si, *Appl. Phys. Lett.*, **91**, 051108.

22. M. Schmid, M. Kaschel, M. Gollhofer, M. Oehme, J. Werner, E. Kasper and J. Schulze (2012). Franz-Keldysh effect of germanium-on-silicon p-i-n diodes within a wide temperature range, *Thin Solid Films*, **525**, 110–114.
23. A. Splett, T. Zinke, K. Petermann, E. Kasper, H. Kibbel, H. J. Herzog and H. Presting (1994). Integration of waveguide and photodetectors in SiGe for 1.3 μm operation, *IEEE Photonics Technol. Lett.*, **6**, 59–61.
24. Y. Kang, et al. (2009). Monolithic germanium/silicon avalanche photodiodes with 340 GHz gain-bandwidth product, *Nat. Photonics*, **3**, 59–63.
25. X. Wang, et al. (2009). 80 GHz bandwidth-gain-product Ge/Si avalanche photodetector by selective Ge growth, *OSA Techn. Dig. Optical Fiber Conference*, paper OMR3.
26. N. Duan, T.-Y. Liow, A. E.-J. Lim, L. Ding and G. Q. Lo (2012). 310 GHz gain-bandwidth product Ge/Si avalanche photodetector for 1550 nm light detection, *Opt. Express*, **20**, 11031.
27. H. Kressel (1982). *Semiconductor Devices for Optical Communication* (Springer-Verlag).
28. B. C. Hsu, C. H. Lin, P. S. Kuo, S. T. Chang, P. S. Chen, C. W. Liu, J. H. Lu and C. H. Kuan (2004). Novel MIS Ge-Si quantum-dot infrared photodetectors, *IEEE Electron Device Lett.*, **25**, 544–546.
29. J. L. Liu, W. G. Wu, A. Balandin, G. L. Jin and K. L. Wang (1992). Intersubband absorption in boron-doped multiple Ge quantum dots, *Appl. Phys. Lett.*, **74**, 185–187.
30. P. S. Kuo, C. H. Lin, C. Y. Peng, Y. C. Fu and C. W. Liu (2007). Transport mechanism of SiGe dot MOS tunneling diodes, *IEEE Electron Device Lett.*, **28**, 596–598.
31. M. H. Liao, C. H. Lee, T. A. Hung and C. W. Liu (2007). The intermixing and strain effects on electroluminescence of SiGe dots, *J. Appl. Phys.*, **102**, 053520-1–353520-5.
32. C. H. Lin and C. W. Liu (2010). Metal-oxide-semiconductor SiGe/Si quantum dot infrared photodetectors with delta doping in different positions, *Thin Solid Films*, **518**, 237–240.
33. S. Klinger, M. Berroth, M. Kaschel, M. Oehme and E. Kasper (2009). Ge on Si p-i-n photodiodes with a 3-dB bandwidth of 49GHz, *IEEE Photonics Technol. Lett.*, **21**, 920–922.
34. O. I. Dosunmu, D. D. Cannon, M. K. Emsley, L. C. Kimerling and M. S. Unlu (2005). High-speed resonant cavity enhance Ge photodetectors on reflecting Si substrates for 1550-nm operation, *IEEE Photonics Technol. Lett.*, **17**, 175–177.

35. M. Rouvière, L. Vivien, X. Le Roux, J. Mangeney, P. Crozat, C. Hoarau, E. Cassan, D. Pascal, S. Laval, J. M. Fédéli, J. F. Damlencourt, J. M. Hartmann and S. Kolev (2005). Ultrahigh speed germanium-on-silicon-on-insulator photodetectors for 1.31 and 1.55 μm operation, *Appl. Phys. Lett.*, **87**, 231109.
36. G. Masini, G. Capellini, J. Witzens and C. Gunn (2008). A 1550 nm, 10 Gbps monolithic optical receiver in 130 nm CMOS with integrated Ge waveguide photodetector, *Proc. of the 5th IEEE International Conference on Group IV Photonics*, 28–30.
37. L. Vivien, D. Marris-Morini, J. Mangeney, P. Crozat, E. Cassan, S. Laval, J. M. Fédéli, J. F. Damlencourt and Y. Lecunff (2008). 42 GHz waveguide germanium-on-silicon vertical PIN photodetector, *Proc. of the 5th IEEE International Conference on Group IV Photonics*, 185–187.
38. D. Suh, S. Kim, J. Joo, G. Kim and I. G. Kim (2008). 35 GHz Ge p-i-n photodetectors implemented using RPCVD, *Proc. of the 5th IEEE International Conference on Group IV Photonics*, 191–193.
39. G. Dehlinger, S. J. Koester, J. D. Schaub, J. O. Chu, Q. C. Ouyang and A. Grill (2004). High-speed germanium-on-SOI lateral PIN photodiodes, *IEEE Photonics Technol. Lett.*, **16**, 2547–2549.
40. J. Yu, E. Kasper and M. Oehme (2006). 1.55- μm resonant cavity enhanced photodiode based on MBE grown Ge quantum dots, *Thin Solid Films*, **508**, 396–398.
41. M. Steglich, et al. (2015). Ge-on-Si photodiode with black silicon boosted responsivity, *Appl. Phys. Lett.*, **107**, 051103.
42. K. Sun, et al. (2018). Low dark current III–V on silicon photodiodes by heteroepitaxy, *Opt. Express*, **26**, 13605.
43. M. Piels and J. E. Bowers (2012). Si/Ge uni-traveling carrier photodetector, *Opt. Express*, **20**, 7488.
44. E. Kasper (2016). Group IV heteroepitaxy on silicon for photonics, *J. Mater. Res.*, **31**, 3639–3648.
45. H. Lin, Z. Luo, T. Gu, L. C. Kimerling, K. Wada, A. Agarwal and J. Hu (2017). Mid-infrared integrated photonics on silicon: a perspective, *Nanophotonics*, **7**, 393–420.
46. D. J. Lockwood, X. Wu, J.-M. Baribeau, S. A. Mala, X. Wang and L. Tsybeskov (2016). Si/SiGe heterointerfaces in one-, two-, and three-dimensional nanostructures: their effect on SiGe light emission, *ECS Trans.*, **75**, 77–96.
47. X. Wang and J. Liu (2018). Emerging technologies in Si active photonics, *J. Semicond.*, **39**, 061001-1–061001-29.

48. S. Assali, et al. (2017). Growth and optical properties of direct band gap Ge/Ge_{0.87}Sn_{0.13} core/shell nanowire arrays, *Nano Lett.*, **17**, 1538–1544.
49. M. Oehme, K. Kostecky, K. Ye, et al. (2014). GeSn-on-Si normal incidence photodetectors with bandwidths more than 40 GHz, *Opt. Express*, **22**, 839.
50. <http://www.aimphotonics.com/pdk/>

References

1. X. Wang and J. Liu (2018). Emerging technologies in Si active photonics, *J. Semicond.*, **39**, 061001-1–061001-29.
2. R. A. Soref and B. R. Bennett (1987). Electrooptical effects in silicon, *IEEE J. Quantum Electron.*, **23**, 123–129.
3. W. Franz (1958). Einfluss eines elektrischen Feldes auf eine optische Absorptionskante, *Z. Naturforsch.*, **13a**, 484–489.
4. L. V. Keldysh (1957). Behaviour of non-metallic crystals in strong electric fields, *JETP*, **33**, 994–1003.
5. A. Frova, P. Handler, F. A. Germano and D. E. Aspnes (1966). Electroabsorption effects at the band edges of silicon and germanium, *Phys. Rev.*, **145**, 575–583.
6. M. Schmid, M. Kaschel, M. Gollhofer, M. Oehme, J. Werner, E. Kasper and J. Schulze (2012). Franz-Keldysh effect of germanium-on-silicon p-i-n diodes within a wide temperature range, *Thin Solid Films*, **525**, 110–114.
7. M. Oehme, K. Kostecky, M. Schmid, M. Kaschel, M. Gollhofer, K. Ye, D. Widmann, R. Koerner, S. Bechler, E. Kasper and J. Schulze (2014). Franz-Keldysh effect in GeSn pin photodetectors, *Appl. Phys. Lett.*, **104**, 161115.
8. R. S. Jacobsen, K. N. Andersen, P. I. Borel, J. Fage-Pedersen, L. H. Frandsen, O. Hansen, M. Kristensen, A. V. Lavrinenko, G. Moulin, H. Ou, C. Peucheret, B. Zsigri and A. Bjarklev (2006). Strained silicon as a new electro-optic material, *Nature*, **441**, 199–202.
9. Y. Ishikawa, K. Wada, D. D. Cannon, J. Liu, H.-C. Luan and L. C. Kimerling (2003). Strain-induced band gap shrinkage in Ge grown on Si substrate, *Appl. Phys. Lett.*, **82**, 13.

10. D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood and C. A. Burrus (1984). Quantum-confined Stark effect, *Phys. Rev. Lett.*, **53**, 2173.
11. J. Stark (1913). Splitting of spectral lines of hydrogen in an electric field, *Scientific talks, Nobel Prize in Physics 1919*.
12. Y.-H. Kuo, Y. K. Lee, Y. Ge, S. Ren, J. E. Roth, T. I. Kamins, D. A. B. Miller and J. S. Harris (2005). Strong quantum-confined Stark effect in germanium quantum-well structures on silicon, *Nature*, **437**, 1334–1337.
13. J F Liu (2016). *Photonics and Electronics with Germanium* (Wiley-VCH Verlag).
14. B. Schmidt, Q. Xu, J. Shakya, S. Manipatruni and M. Lipson (2007). Compact electro-optic modulator on silicon-on-insulator substrates using cavities with ultra-small modal volumes, *Opt. Express*, **15**, 3140–3148.
15. X. Tu (2008). Study on the silicon-on-insulator optical waveguide electro-optical modulator, PhD thesis, Institute of Semiconductors, Chinese Academy of Sciences.
16. A. R. M. Zain, N. P. Johnson, M. Sorel and R. M. De La Rue (2008). Ultra high quality factor one dimensional photonic crystal/photonic wire micro-cavities in silicon-on-insulator (SOI), *Opt. Express*, **16**, 12084–12089.
17. Q. Xu, B. Schmidt, S. Pradhan and M. Lipson (2005). Micrometre-scale silicon electro-optic modulator, *Nature*, **435**, 325–328.
18. L. Friedman, R. A. Soref and J. P. Lorenzo (1988). Silicon double-injection electrooptic modulator with junction gate control, *J. Appl. Phys.*, **63**, 1831–1839.
19. A. Cutolo, M. Iodice, P. Spirito and L. Zeni (1997). Silicon electro-optic modulator based on a three terminal device integrated on a low-loss single-mode SOI waveguide, *J. Lightwave Technol.*, **15**, 505–518.
20. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu and M. Paniccia (2004). High-speed silicon optical modulator based on a metaloxide-semiconductor capacitor, *Nature*, **427**, 615–618.
21. Q. F. Xu, S. Manipatruni, B. Schmidt, J. Shakya and M. Lipson (2007). 12.5 Gbit/s carrier-injection-based silicon micro-ring modulators, *Opt. Express*, **15**, 430–436.

22. L. Liao, D. Samara-Rubio, M. Morse, A. Liu, D. Hodge, D. Rubin, U. D. Keil and T. Franck (2005). High speed silicon Mach-Zehnder modulator, *Opt. Express*, **13**, 3129–3135.
23. F. Y. Gardes, G. T. Reed, N. G. Emerson and C. E. Png (2005). A sub-micron depletion-type photonic modulator in silicon on insulator, *Opt. Express*, **13**, 8845–8854.
24. A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky and M. Paniccia (2007). High-speed optical modulation based on carrier depletion in a silicon waveguide, *Opt. Express*, **15**, 660–668.
25. W. M. J. Green, M. J. Rooks, L. Sekaric and Y. A. Vlasov (2007). Ultra-compact, low RF power, 10 Gb/s Silicon Mach-Zehnder modulator, *Opt. Express*, **15**, 17106–17113.
26. E. A. J. Marcatili (1969). Dielectric rectangular waveguide and directional coupler for integrated optics, *Bell Syst. Tech. J.*, **48**, 2071–2102.
27. G.-S. Jeong, W. Bae and D.-K. Jeong (2017). Review of CMOS integrated circuit technologies for high-speed photo-detection, *Sensors*, **17**, 1962.
28. P. De Heyn, V. I. Kopp, S. A. Srinivasan, et al. (2017). Ultra-dense 16×56 Gb/s NRZ GeSi EAM-PD arrays coupled to multicore fiber for short-reach 896Gb/s optical links, *Optical Fiber Communication Conference*, Th1B.7.
29. J. Verbist, M. Verplaetse, S. A. Srinivasan, et al. (2017). First real-time 100-Gb/s NRZ-OOK transmission over 2 km with a silicon photonic electro-absorption modulator. *Optical Fiber Communication Conference*, Th5C.4.
30. M. Oehme, E. Kasper and J. Schulze (2013). GeSn heterojunction diode: detector and emitter in one device, *ECS J. Solid State Sci. Technol.*, **2**, 76–78.

References

1. X. Sun, J. Liu, L. C. Kimerling and J. Michel (2009). Room-temperature direct bandgap electroluminescence from Ge-on-Si light-emitting diodes, *Opt. Lett.*, **34**, 1198.
2. E. Kasper, M. Oehme, J. Werner, T. Aguirov and M. Kittler (2012). Direct band gap luminescence from Ge on Si pin diodes, *Front. Optoelectron.*, **5**, 256.
3. P. Moontragoon, R. A. Soref and Z. Ikonc (2012). The direct and indirect bandgaps of unstrained $\text{Si}_x\text{Ge}_{1-x-y}\text{Sn}_y$ and their photonic device applications, *J. Appl. Phys.*, **112**, 073106.
4. P. Boucaud, M. El Kurdi and J. M. Hartmann (2004). Photoluminescence of a tensilely strained silicon quantum well on a relaxed SiGe buffer layer, *Appl. Phys. Lett.*, **85**, 46.
5. E. Kasper, J. Werner, M. Oehme, S. Escoubas, N. Burle and J. Schulze (2012). Growth of silicon based germanium tin alloys, *Thin Solid Films*, **520**, 3195.
6. E. Kasper, N. Burle, S. Escoubas, J. Werner, M. Oehme and K. Lyutovic (2012). Strain relaxation of metastable SiGe/Si: investigation with two complementary X-ray techniques, *J. Appl. Phys.*, **111**, 063507.
7. V. R. D'Costa, C. S. Cook, A. G. Birdwell, C. L. Littler, M. Canonico, S. Zollner, J. Kouvetakis and J. Menendez (2006). Optical critical points of thin-film $\text{Ge}_{1-y}\text{Sn}_y$ alloys: a comparative $\text{Ge}_{1-y}\text{Sn}_y/\text{Ge}_{1-x}\text{Si}_x$ study, *Phys. Rev. B*, **73**, 125207.
8. S. Alberi, J. Blackberg, L. D. Bell, S. Nikzad, K. M. Yu, O. D. Dubon and W. Walukiewicz (2008). Band anticrossing in highly mismatched $\text{Sn}_x\text{Ge}_{1-x}$ semiconducting alloys, *Phys. Rev. B*, **77**, 073202.
9. L. Vegard (1921). Die Konstitution der Mischkristalle und die Raumfüllung der Atome, *Z. Phys.* (in German) **5**, 17–26.
10. R. S. Bauer and G. Margaritondo (1987). Probing semiconductor/semiconductor interfaces, *Phys. Today*, **40**, 27.
11. G. Sun, R. A. Soref and H. H. Cheng (2010). Design of a Si-based lattice-matched room-temperature GeSn/GeSiSn multi-quantum-well mid-infrared laser diode, *Opt. Express*, **18**, 19957.
12. M. Oehme, M. Schmid, M. Kaschel, M. Gollhofer, D. Widmann, E. Kasper and J. Schulze (2012). GeSn p-i-n detectors integrated on Si with up to 4% Sn, *Appl. Phys. Lett.*, **101**, 141110.
13. J. Mathews, R. Roucka, J. Xie, S.-Q. Yu, J. Menendez and J. Kouvetakis (2009). Extended performance GeSn/Si(100) p-i-n photodetectors for

- full spectral range telecommunication applications, *Appl. Phys. Lett.*, **95**, 133506.
14. S. Su, B. Cheng, C. Xue, W. Wang, Q. Cao, H. Xue, W. Hu, G. Zhang, Y. Zuo and Q. Wang (2011). GeSn p-i-n photodetector for all telecommunication bands detection, *Opt. Express*, **19**, 6400.
 15. J. Werner, M. Oehme, M. Schmid, M. Kaschel, A. Schirmer, E. Kasper and J. Schulze (2011). Germanium-tin p-i-n photodetectors integrated on silicon grown by molecular beam epitaxy, *Appl. Phys. Lett.*, **98**, 061108.
 16. R. Roucka, J. Mathews, R. Beeler, J. Tolle, J. Kouvetakis and J. Menendez (2011). Direct gap electroluminescence from Si/Ge_{1-y}Sn_y p-i-n heterostructure diodes, *Appl. Phys. Lett.*, **98**, 061109.
 17. J. Matthews, R. Roucka, J. Xie, S.-Q. Yu, J. Menendez and J. Kouvetakis (2009). Extended performance GeSn/Si(100) p-i-n photodetectors for full spectral range telecommunication applications, *Appl. Phys. Lett.*, **95**, 133506.
 18. M. Oehme, J. Werner, M. Gollhofer, M. Schmid, M. Kaschel, E. Kasper and J. Schulze (2011). Room-temperature electroluminescence from GeSn light-emitting pin diodes on Si, *IEEE Photonics Technol. Lett.*, **23**, 1751–1753.
 19. M. Oehme, E. Kasper and J. Schulze (2012). GeSn photodetection and electroluminescence devices on Si, *ECS Trans.*, **50**(9), 583–590.
 20. T. Arguirov (2014). Pers. Communication.
 21. H. Lin, R. Chen, W. Lu, Y. Huo, T. I. Kamins and J. S. Harris (2012). Investigation of the direct band gaps in Ge_{1-x}Sn_x alloys with strain control by photorefectance spectroscopy, *Appl. Phys. Lett.*, **100**, 102109.
 22. S.-Q. Liu and S.-T. Yen (2019). Extraction of eight-band $k \cdot p$ parameters from empirical pseudopotentials for GeSn, *J. Appl. Phys.*, **125**, 245701.
 23. H. Tran, W. Du, S. A. Ghetmiri, A. Mosleh, G. Sun, R. A. Soref, J. Margetis, J. Tolle, B. Li, H. A. Naseem and S.-Q. Yu (2016). Systematic study of Ge_{1-x}Sn_x absorption coefficient and refractive index for the device applications of Si-based optoelectronics, *J. Appl. Phys.*, **119**, 103106.
 24. C. Xu, P. M. Wallace, D. A. Ringwala, S. L. Y. Chang, C. D. Poweleit, J. Kouvetakis and J. Menéndez (2019). Mid-infrared (3–8 μm) Ge_{1-y}Sn_y alloys (0.15 < y < 0.30): synthesis, structural, and optical properties, *Appl. Phys. Lett.*, **114**, 212104.
 25. G. Sun (2011). ICSI-7, Invited Talk.
 26. E. Kasper and M. Oehme (2015). Germanium tin light emitters on silicon, *Jpn. J. Appl. Phys.*, **54**, 04DG11.

References

1. N. Koshida (2007). Luminescence and related properties of nanocrystalline porous silicon, in *Landolt-Boernstein, New Series*, Vol. III, 34C3, Semiconductor Quantum Structures-Optical Properties (Springer-Verlag).
2. E. Kasper, H.-J. Herzog and H. Kibbel (1975). A one-dimensional SiGe superlattice grown by UHV epitaxy, *Appl. Phys.*, **8**, 199.
3. L. T. Canham (1990). Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers, *Appl. Phys. Lett.*, **57**, 1046.
4. L. Pavesi, L. Dal Negro, C. Mazzoleni, G. Franzo and F. Priolo (2000). Optical gain in silicon nanocrystals, *Nature*, **408**, 440.
5. U. Gnutzmann and K. Clausecker (1974). Theory of direct optical transitions in an optical indirect semiconductor with a superlattice structure, *Appl. Phys.*, **3**, 9.
6. H. Brugger, G. Abstreiter, H. Jorke, H. J. Herzog and E. Kasper (1986). Dispersion of folded phonons in superlattices, *Phys. Rev. B*, **33**, 5928.
7. R. Zachai, K. Eberl, G. Abstreiter, E. Kasper and H. Kibbel (1990). Photoluminescence in short-period Si/Ge strained layer superlattices, *Phys. Rev. Lett.*, **64**, 1055.
8. H. Presting, U. Menzinger and H. Kibbel (1993). Electro- and photoluminescence studies from ultrathin Si/Ge superlattices, *J. Vac. Sci. Technol. B*, **11**, 1110.
9. B. Corbett, C. Bower, A. Fecioru, M. Mooney, M. Gubbings and J. Justice (2013). Strategies for integration of lasers on silicon, *Semicond. Sci. Technol.*, **28**, 094001.

10. A. W. Fang, B. R. Koch, R. Jones, E. Lively, P. Liang, Y. K. Kuo and J. E. Bowers (2008). A distributed Bragg reflector silicon evanescent laser, *IEEE Photonics Technol. Lett.*, **20**, 1667.
11. J. Liu, X. Sun, R. Camacho-Aguilera, L. C. Kimerling and J. Michel (2010). Ge-on-Si laser operating at room temperature, *Opt. Lett.*, **35**, 679–681.
12. Jr. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bassette, M. Romangnoli, L. C. Kimerling and J. Michel (2012). An electrical pumped Ge laser, *Opt. Express*, **20**, 11316.
13. H. C. Casey and M. B. Panish (1978). *Heterostructure Lasers: Fundamental Principles* (Academic Press, New York).
14. C. Weisbuch (1987). Optical properties of quantum wells, in *Physics and Applications of Quantum Wells and Superlattices*, E. E. Mendez and K. von Klitzing, eds., NATO ASI Series B170 (Plenum Press), pp. 261–299.
15. M. Asada, Y. Miyamoto and Y. Suematsu (1986). Gain and the threshold of three-dimensional quantum box lasers, *IEEE J. Quantum Electron.*, **QE-22**, 1915.
16. W. T. Tsang (1984). Heterostructure semiconductor lasers prepared by MBE, *IEEE J. Quantum Electron.*, **QE-20**, 1119.
17. Y. Arakawa and A. Yariv (1985). Theory of gain, modulation response and spectral linewidth in AlGaAs quantum well lasers, *IEEE J. Quantum Electron.*, **QE-21**, 1666.
18. G. Mak and H. M. van Driel (1994). Femtosecond transmission spectroscopy at the direct band edge of germanium, *Phys. Rev. B*, **49**, 16817.
19. X. Q. Zhou, H. M. van Driel and G. Mak (1994). Femtosecond kinetics of photoexcited carriers in germanium, *Phys. Rev. B*, **50**, 5226.
20. S. A. Claussen, E. Tasyurek, J. E. Roth and D. A. B. Miller (2010). Measurement and modeling of ultrafast carrier dynamics and transport in germanium/silicon-germanium quantum wells, *Opt. Express*, **18**, 25596.
21. X. Wang, L. C. Kimerling, J. Michel and J. Liu (2013). Large inherent optical gain from the direct gap transition of Ge thin films, *Appl. Phys. Lett.*, **102**, 131116.
22. J. S. Blackmore (1982). Approximations for Fermi-Dirac integrals, *Solid State Electron.*, **25**, 1067.
23. S. M. Sze (1981). *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York).

24. E. Kasper, M. Oehme, J. Werner, T. Aguirov and M. Kittler (2012). Direct bandgap luminescence from Ge on Si pin diodes, *Front. Optoelectron.*, **5**, 256.
25. R. Neumann and G. Abstreiter (2000). Effective masses of electrons and holes in SiGe, in *EMIS Datareview Series*, Vol. 24 (INSPEC (IEE), London).
26. H. Kroemer (1978). The Einstein relation for degenerate carrier concentrations, *IEEE Trans.*, **ED-25**, 850.
27. E. Kasper and M. Oehme (2015). Germanium tin light emitters on silicon, *Jap. J. Appl. Phys.*, **54**, 04DG11.
28. R. Geiger, T. Zabel and H. Sigg (2015). Group IV direct bandgap photonics: methods, challenges and opportunities, *Front. Mater.*, **2**, 52.
29. J. Liu, R. Camacho-Aguilera, J. T. Bessette, X. Sun, S. Wang, Y. Cai, L. C. Kimerling and J. Michel (2012). Ge-on-Si optoelectronics, *Thin Solid Films*, **520**, 3354–3360.
30. G. Sun, R. A. Soref and H. H. Cheng (2010). Design of an electrically pumped SiGeSn/GeSn/SiGeSn double heterostructure mid-infrared laser diode, *Jpn. J. Appl. Phys.*, **108**, 033107.
31. T. Aguirov, M. Kittler, M. Oehme, N. V. Abrasimov, E. Kasper and J. Schulze (2011). Room temperature direct band gap emission from an unstrained Ge pin LED, *Solid State Phenom.*, **178**, 25.
32. D. S. Sukhdeo, S. Gupta, K. C. Saraswat, B. Dutt and D. Nam (2016). Impact of minority carrier lifetime on the performance of strained germanium light sources, *Opt. Commun.*, **364**, 233–237.
33. www.ioffe.ru/SVA/NSM/Semicond/Ge/Electronic.html
34. X. Sun (2009). Ge-on-Si light-emitting materials and devices for silicon photonics, PhD thesis, MIT.
35. J. Liu, X. Sun, D. Pan, X. Wang, L. C. Kimerling, T. L. Koch and J. Michel (2007). Tensile-strained, n-type Ge as a gain medium for monolithic laser integration on Si, *Opt. Express*, **15**, 11272.
36. P. Y. Yu and M. Cardona (1996). *Fundamentals of Semiconductors: Physics and Materials Properties* (Springer-Verlag, Berlin).
37. C. F. Klingshirn (2012). *Semiconductor Optics*, 4th ed. (Springer-Verlag, Berlin).
38. C. Xu, J. D. Gallagher, C. L. Senaratne, J. Menendez and J. Kouvetakis (2016). Optical properties of Ge-rich $\text{Ge}_{1-x}\text{Si}_x$ alloys: compositional dependence of the lowest direct and indirect gaps, *Phys. Rev. B*, **93**, 125206.

39. P. H. Lim, S. Park, Y. Ishikawa and K. Wada (2009). Enhanced direct bandgap emission in germanium by micromechanical strain engineering, *Opt. Express*, **17**, 16358.
40. S. Fathpour (2012). Emerging heterogeneous integrated platforms on silicon, *Nanophotonics*, **4**(1).
41. A. Spott, M. Davenport, J. Peters, J. Bovington, M. J. R. Heck, E. J. Stanton, I. Vurgaftman, J. Meyer and J. E. Bowers (2015). Heterogeneously integrated 2.0 μm CW hybrid silicon lasers at room temperature, *Opt. Lett.*, **40**, 1480.
42. C. Zhang, S. Srinivasan, Y. Tang, M. R. J. Heck, M. L. Davenport and J. E. Bowers (2014). Low threshold and high speed short cavity distributed feedback hybrid silicon lasers, *Opt. Express*, **22**, 10202–10209.
43. H. T. Hattori, C. Seassal, E. Touraille, P. Rojo-Romeo, X. Letartre, G. Hollinger, P. Viktorovitch, L. Di Cioccio, M. Zussy, L. El Melhaoui and J. M. Fedeli (2006). Heterogeneous integration of microdisk lasers on silicon strip waveguides for optical interconnects, *IEEE Photonics Technol. Lett.*, **18**, 223.
44. S. Keyvaninia, C. Roelkens, D. Van Thourhout, C. Jany, M. Lamponi, A. L. Liepvre, F. Lelarge, D. Make, G. H. Duan, D. Bordel and J. M. Fedeli (2013). Demonstration of a heterogeneously integrated III-V/SOI single wavelength tuneable laser, *Opt. Express*, **38**, 5434.
45. Y. Wan, Q. Li, A. Y. Liu, A. C. Gossard, J. E. Bowers, E. L. Hu and K. M. Lau (2016). Temperature characteristics of epitaxially grown InAs quantum dot micro-disk lasers on silicon for on-chip light sources, *Appl. Phys. Lett.*, **109**, 011104.
46. A. Y. Liu, C. Zhang, J. Norman, A. Snyder, D. Lubyshev, J. M. Fastenau, A. W. K. Liu, A. C. Gossard and J. E. Bowers (2014). High performance continuous wave 1.3 μm quantum dot laser on silicon, *Appl. Phys. Lett.*, **104**, 041104.
47. Z. Zhau, B. Yin and J. Michel (2015). On-chip light sources for silicon photonics, *Light Sci. Appl.*, **4**, e358.
48. L. Carroll, P. Friedli, S. Neuenschwander, H. Sigg, S. Cecchi, F. Isa, D. Christina, G. Isella, Y. Fedoryshyn and J. Faist (2012). Direct-gap gain and optical absorption in germanium correlated to the density of photo excited carrier, doping and strain, *Phys. Rev. Lett.*, **109**, 057402.
49. R. Koerner, M. Oehme, M. Gollhofer, M. Schmid, K. Kostecky, S. Bechler, W. Widmann, E. Kasper and J. Schulze (2015). Electrically pumped lasing from Ge Fabry-Perot resonators on Si, *Opt. Express*, **23**, 14815.

50. S. Wirths, R. Geiger, N. von den Driesch, G. Mussler, T. Stoica, S. Mantl, Z. Ikonik, M. Luysberg, S. Chiussi, J. M. Hartmann, H. Sigg, J. Faist, D. Buca and D. Grützmacher (2015). Lasing in direct-bandgap GeSn alloy grown on Si, *Nat. Photonics*, **9**, 88–92.
51. E. Kasper (2016). Group IV heteroepitaxy on Si for photonics, *J. Mater. Res.*, **31**, 3639–3649.
52. E. Kasper and V. Stefani (2008). Device with optical coupling window and fabrication method for this device, German patent, No. 102008051625 (in German).
53. J. Zhang, B. Haq, J. O’Callaghan, A. Gocalinska, E. Peluchi, A. J. Trinade, B. Corbette, G. Morthier and G. Roelkens (2018). Transfer-printing-based integration of a III-V-on-silicon distributed feedback laser, *Opt. Express*, **26**, 8821–8830.
54. B. Dutt, D. S. Sukhdeo, D. Nam, B. M. Vulovic, Z. Yuan and K. C. Saraswat (2012). Roadmap to an efficient germanium-on-silicon laser: strain vs. n-type doping, *IEEE Photonics J.*, **4**, 2002.
55. Z. Zhou, B. Yin and J. Michel (2015). On-chip light sources for silicon photonics, *Light Sci. Appl.*, **4**, e358.
56. Y. Cai, Z. Han, X. Wang, R. E. Camacho-Aguilera, L. C. Kimerling, J. Michel and J. Liu (2013). Analysis of threshold current behavior for bulk and quantum well germanium laser structures, *IEEE J. Sel. Top. Quantum Electron.*, **19**, 1901009.
57. D. Stange, S. Wirths, N. von den Driesch, G. Mussler, T. Stoica, Z. Ikonik, J. M. Hartmann, S. Mantl, D. Grützmacher and D. Buca (2015). Optical transitions in direct-bandgap $\text{Ge}_{1-x}\text{Sn}_x$ alloys, *ACS Photonics Lett.*, **2**, 1539–1545.
58. V. Reboud, et al. (2018). Optically pumped GeSn micro-disks with 16% Sn lasing at 3.1 μm up to 180 K, *Appl. Phys. Lett.*, **111**, 092101.
59. R. Loo, Y. Shimura, S. Ike, A. Vohra, T. Stoica, D. Stange, D. Buca, D. Kohen, J. Margetis and J. Tolle (2018). Epitaxial GeSn: impact of process conditions on material quality, *Semicond. Sci. Technol.*, **33**, 114010 (9pp).
60. N. von den Driesch, et al. (2018). Advanced GeSn/SiGeSn group IV heterostructure lasers, *Adv. Sci.*, **5**, 1700955.
61. P. O. Vaccaro, M. I. Alonso, M. Garriga, J. Gutiérrez, D. Però, M. R. Wagner, J. S. Reparaz, C. M. Sotomayor Torres, X. Vidal, E. A. Carter, P. A. Lay, M. Yoshimoto and A. R. Goñi (2018). Localized thinning for strain concentration in suspended germanium membranes and optical method for precise thickness measurement, *AIP Adv.*, **8**, 115131.

62. G. Niu, G. Capellini, M. A. Schubert, T. Niermann, P. Zaumseil, J. Katzer, H.-M. Krause, O. Skibitzki, M. Lehmann, Y.-H. Xie, H. von Känel and T. Schroeder (2016). Dislocation-free Ge nano-crystals via pattern independent selective Ge heteroepitaxy on Si nano-tip wafers, *Sci. Rep.*, **6**, 22709.
63. F. T. Armand Pilon et al. (2019). Lasing in strained germanium microbridges, *Nat. Commun.*, **10**, 2724.
64. J. Chrétien et al. (2019). GeSn lasers covering a wide wavelength range thanks to uniaxial tensile strain, *ACS Photon.*, **6**, 2462–2469.
65. A. Elbaz et al. (2020). Ultra-low-threshold continuous-wave and pulsed lasing in tensile-strained GeSn alloys, *Nat. Photon.*, arXiv:2001.04927.
66. Y. Zhou et al. (2020). Electrically injected GeSn lasers on Si operating up to 100 K, arXiv 2004.09402.

References

1. E. Mounier and J.-L. Malinge (2018). Yole annual report, http://www.yole.fr/Silicon Photonics_Market_Applications.aspx
2. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bassette, M. Romagnoli, L. C. Kimmerling and J. Michel (2012). An electrical pumped Ge laser, *Opt. Express*, **20**, 11316.
3. R. Koerner, M. Oehme, M. Gollhofer, M. Schmid, K. Kosteki, S. Bechler, W. Widmann, E. Kasper and J. Schulze (2015). Electrically pumped lasing from Ge Fabry-Perot resonators on Si, *Opt. Express*, **23**, 14815.
4. S. Wirths, R. Geiger, N. von den Driesch, G. Mussler, T. Stoica, S. Mantl, Z. Ikonic, M. Luysberg, S. Chiussi, J. M. Hartmann, H. Sigg, J. Faist, D. Buca and D. Grützmacher (2015). Lasing in direct-bandgap GeSn alloy grown on Si, *Nat. Photonics*, **9**, 88–92.

5. E. Kasper (2016). Group IV heteroepitaxy on silicon for photonics, *J. Mater. Res.*, **31**, 3639–3648.
6. S. Gupta, E. Simoen, R. Loo, Y. Shimura, C. Porret, F. Gencarelli, K. Paredis, H. Bender, J. Lauwaert, H. Vrielinck and M. Heyns (2018). Electrical properties of extended defects in strain relaxed GeSn, *Appl. Phys. Lett.*, **113**, 022102.
7. T. S. Perova, E. Kasper, M. Oehme, S. Cherevkov and J. Schulze (2017). Features of polarized Raman spectra for homogeneous and non-homogeneous compressively strained GeSn alloys, *J. Raman Spectrosc.*, **48**, 993–1001.
8. S. Assali, J. Nicolas, S. Mukherjee, A. Dijkstra and O. Moutanabbir (2018). Atomically uniform Sn-rich GeSn semiconductors with 3.0–3.5 μm room-temperature optical emission, *Appl. Phys. Lett.*, **112**, 251903.
9. L. Kormos, M. Kratzer, K. Kosteki, M. Oehme, T. Sikola, E. Kasper, J. Schulze and C. Teichert (2017). Surface analysis of epitaxially grown GeSn alloys with Sn contents between 15% and 18%, *Surf. Interface Anal.*, **49**, 297–302.
10. W. Dou, M. Benamara, A. Mosleh, J. Margetis, P. Grant, Y. Zhou, S. Al-Kabi, W. Du, J. Tolle, B. Li, M. Mortazavi and S.-Q. Yu (2018). Investigation of GeSn strain relaxation and spontaneous composition gradient for low-defect and high-Sn alloy growth, *Sci. Rep.*, **8**, 5640.
11. M. Yako, Y. Ishikawa, E. Abe and K. Wada (2018). Reduction of threading dislocations by image force in Ge selective epilayers on Si, *Proc. SPIE 10823, Nanophotonics and Micro/Nano Optics IV*, 108230F, doi:10.1117/12.2501081.
12. K. R. Khiantge, J. S. Rathore, V. Sharma, S. Bhunia, S. Das, R. S. Fandan, R. S. Pokharia, A. Laha and S. Mahapatra (2017). Dislocation density and strain-relaxation in $\text{Ge}_{1-x}\text{Sn}_x$ layers grown on Ge/Si (001) by low-temperature molecular beam epitaxy, *J. Cryst. Growth*, **470**, 135–142.
13. V. P. Martovitsky, Yu. A. Aleshchenko, V. S. Krivobok, A. V. Muratov, A. V. Klekovkin and A. B. Mehiya (2018). Molecular beam epitaxy of Si-Ge-Sn heterostructures for monolithically integrated optoelectronic devices based on silicon, *Bull. Russ. Acad. Sci.*, **82**, 418–423.
14. W. Dou, M. Benamara, A. Mosleh, J. Margetis, P. Grant, Y. Zhou, S. Al-Kabi, W. Du, J. Tolle, B. Li, M. Mortazavi and S.-Q. Yu (2018). Investigation of GeSn strain relaxation and spontaneous composition gradient for low-defect and high-Sn alloy growth, *Sci. Rep.*, **8**, 5640.
15. D. Zhang, Z. Liu, D. Zhang, X. Zhang, J. Zhang, J. Zheng, Y. Zuo, C. Xue, C. Li, S. Oda, B. Cheng and Q. Wang (2018). Sn-guided defect-free GeSn

- lateral growth on Si by molecular beam epitaxy, *J. Phys. Chem. C*, **119**, 17842–17847.
16. S. Bao, D. Kim, C. Onwukaeme, S. Gupta, K. Saraswat, K. H. Lee, Y. Kim, D. Min, Y. Jung, H. Qiu, H. Wang, E. A. Fitzgerald, C. S. Tan and D. Nam (2017). Low-threshold optically pumped lasing in highly strained germanium nanowires, *Nat. Commun.*, **8**, 1845, doi: 10.1038/s41467-017-02026.
 17. R. A. Minamisawa, M. J. Süess, R. Spolenak, J. Faist, C. David, J. Gobrecht, K. K. Bourdelle and H. Sigg (2012). Top-down fabricated silicon nanowires under tensile elastic strain up to 4.5%, *Nat. Commun.*, **3**, 1096, doi: 10.1038/ncomms2102.
 18. R. Koerner, M. Oehme, M. Gollhofer, K. Kostecky, M. Schmid, S. Bechler, D. Widmann, E. Kasper and J. Schulze (2014). *Proc. 7th International Silicon-Germanium Technology and Device Meeting (ISTDM)*, Singapore, 121–122.
 19. M. Amato, M. Palummo, R. Rurali and S. Ossicini (2014). Silicon–germanium nanowires: chemistry and physics in play, from basic principles to advanced applications, *Chem. Rev.*, **114**, 1371–1412.
 20. S. Assali, A. Dijkstra, A. Li, S. Koelling, M. A. Verheijen, L. Gagliano, N. von den Driesch, D. Buca, P. M. Koenraad, J. E. M. Haverkort and E. P. A. M. Bakkers (2017). Growth and optical properties of direct band gap Ge/Ge_{0.87}Sn_{0.13} core/shell nanowire arrays, *Nano Lett.*, **17**, 1538–1544.
 21. Y. Shimura, S. A. Srinivasan and R. Loo (2016). Design requirements for group-IV laser based on fully strained Ge_{1-x}Sn_x embedded in partially relaxed Si_{1-y-z}Ge_ySn_z buffer layers, *ECS J. Solid State Sci. Technol.*, **5**, Q140–Q143.
 22. B. Mukhopadhyaya, G. Sen, S. De, R. Basu, V. Chakraborty and P. K. Basu (2018). Calculated characteristics of a transistor laser using alloys of Gr-IV elements, *Phys. Status Solidi B*, 1800117.
 23. G.-S. Jeong, W. Bae and D.-K. Jeong (2017). Review of CMOS integrated circuit technologies for high-speed photo-detection, *Sensors*, **17**, 1962.
 24. X. Wang and J. Liu (2018). Emerging technologies in Si active photonics, *J. Semicond.*, **39**, 061001, doi: 10.1088/1674-4926/39/6/061001.
 25. M. Oehme, E. Kasper and J. Schulze (2013). GeSn heterojunction diode: detector and emitter in one device, *ECS J. Solid State Sci. Technol.*, **2**, 76–78.
 26. M. Oehme, K. Kostecky, M. Schmid, M. Kaschel, M. Gollhofer, K. Ye, D. Widmann, R. Koerner, S. Bechler, E. Kasper and J. Schulze (2014). Franz-Keldysh effect in GeSn pin photodetectors, *Appl. Phys. Lett.*, **104**, 161115.

27. M. Oehme, D. Widmann, K. Kostecky, P. Zaumseil, B. Schwartz, M. Gollhofer, R. Koerner, S. Bechler, M. Kittler, E. Kasper and J. Schulze (2014). GeSn/Ge multi quantum well photodetectors on Si substrates, *Opt. Lett.*, **39**, 4711–4714.
28. X. Chen, M. M. Milosevic, S. Stankovic, S. Reynolds, T. D. Bucio, K. Li, D. J. Thompson, F. Gardes and G. T. Reed (2018). The emergence of silicon photonics as a flexible technology platform, *Proc. IEEE*, doi: 1.11090/JPROC.2018.2854372.
29. K. Sun, D. Jung, C. Shang, A. Liu, J. Morgan, J. Zang, Q. Li, J. Klamkin, J. E. Bowers and A. Belin (2018). Low dark current III-V on silicon photodiodes by heteroepitaxy, *Opt. Express*, **26**, 13605.
30. J. Zhang, B. Haq, J. O'Callaghan, A. Gocalinska, E. Peluchi, A. J. Trinade, B. Corbette, G. Morthier and G. Roelkens (2018). Transfer-printing-based integration of a III-V-on-silicon distributed feedback laser, *Opt. Express*, doi: 10.1364/OE.26.008821.
31. Z. Qi, H. Sun, M. Luo, Y. Jung and D. Nam (2018). Strained germanium nanowire optoelectronic devices for photonic integrated circuits, *J. Phys.: Condens. Matter*, **30**, 334004.
32. S. Gupta, E. Simoen, R. Loo, Y. Shimura, C. Porret, F. Gencarelli, K. Paredis, H. Bender, J. Lauwaert, H. Vrielinck and M. Heyns (2018). Electrical properties of extended defects in strain relaxed GeSn, *Appl. Phys. Lett.*, **113**, 022102, doi: 10.1063/1.5034573.
33. O. Nakatsuka, N. Tsutsui, Y. Shimura, S. Takeuchi, A. Sakai and S. Zaima (2010). Mobility behavior of $\text{Ge}_{1-x}\text{Sn}_x$ layers grown on silicon-on-insulator substrates, *Jpn. J. Appl. Phys.*, **49**, 04DA10.
34. P. Onufrijs, personal information.
35. D. V. Guzатов, S. V. Gaponenko and H. V. Demir (2018). Plasmonic enhancement of electroluminescence, *AIP Adv.*, **8**, 015324.
36. M. Gu, P. Bai, H. S. Chu and E.-P. Li (2012). A design of subwavelength CMOS compatible plasmonic photodetector for nano-photonics integrated circuits, *IEEE Photonics Technol. Lett.*, **24**, 515–517.
37. P. Cheben, R. Halir, J. H. Schmid, H. A. Atwater and D. R. Smith (2018). Subwavelength integrated photonics, *Nature*, **560**, 565–572.
38. L. Zhang, A. M. Agarwal, L. C. Kimerling and J. Michel (2014). Nonlinear group IV photonics based on silicon and germanium: from near-infrared to mid-infrared, *Nanophotonics*, **3**, 247–268.
39. R. Osgood Jr., J. B. Driscoll, W. Astar, X. Liu, J. I. Dadap, W. M. J. Green, Y. A. Vlasov and G. M. Carter (2010). Nonlinear silicon photonics, *SPIE Newsroom*, doi: 10.1117/2.1201004.002934.

40. B. Yoo, R. P. Scott, D. J. Geisler, N. K. Fontaine and F. M. Soares (2012). Terahertz information and signal processing by RF-photonics, *IEEE Trans. Terahertz Sci. Technol.*, **2**, 167–176.
41. A. W. M. Mohammad (2019). Integrated photonics for millimetre wave transmitters and receivers, PhD thesis, University College London, <https://www.researchgate.net/publication/334082977>.