Photonics in a Time of Rapid Growth: Silicon Based Optoelectronics in China

Zhiping Zhou, Weibiao Chen, Xiwen He, and Deyue Ma

Abstract—**Silicon-based optoelectronics (SBO), combining the advantages of both microelectronics and optoelectronics, has entered a period of rapid development. Applications based on SBO have expanded from traditional communication field to other fields such as sensing, computing, and artificial intelligence. Although the SBO technology started relatively late in China, it has developed rapidly in recent years due to continuous investment and improved industrial structure. This article first reviews the early activities, and then, summarizes the current status of SBO in China. It provides a comprehensive analysis of academic and industrial advancements in recent years and discusses future development directions and main challenges.**

Index Terms—**Silicon-based optoelectronics, microelectronics, optoelectronics, SBO academic research in China, SBO industrial development in China.**

I. Introduction

THE invention of the world's first transistor by William Shockley and others at Bell Labs in the 1940s marked the beginning of the microelectronics era [1]. Over the following decades, microelectronics technology has steadily advanced according to Moore's Law [2], playing a crucial role in information processing. Integrated circuit chips have been evolving towards larger scales and higher performance. However, as device integration improves further, the inherent limitations of electrical interconnection will rapidly increase the heating of chips, causing problems like crosstalk, noise, energy consumption and delays, which impede normal operation of the chips [3]. Additionally, current micro/nano processing equipment is approaching its process limit, making it challenging to increase the chip's operating frequency and integration level by reducing linewidth [4]. Moreover, deep nanoscale linewidth faces unprecedented challenges in avoiding quantum tunneling between adjacent wires caused by quantum effects [5]. Consequently, relying solely on electrons as information carriers, microelectronics technology confronts substantial theoretical and technological bottlenecks that hinder further progress in the information society [6].

Photons have no static mass nor interference with each other, therefore, various properties of photons, such as wave- length, polarization, mode, etc., can all be used to facilitate communication [7]. This is why optical information transmis- sion enables higher bandwidth, along with fast processing speed and immunity to electromagnetic interference. Nev- ertheless, integrated optics still encounter several technical challenges in practical applications, such as diffraction limiting the size of optical components in integrated optics, and the lack of standardized preparation techniques leading to high manufacturing costs [8]. To fully leverage the benefits of micro- electronics and optoelectronics, the concept of optoelectronic hybrid integrated chip systems was introduced in the 1990 s by Soref in which optoelectronic devices are all composed of III-V semiconductors and are separately integrated with silicon- based electronic circuits [9]. Unfortunately, in the era of Big Data, discrete package solutions no longer meet the information processing requirements of low energy consumption, low cost, and high speed. Hence, the need for heterogeneous integration of optoelectronic and electronic technologies on the same silicon substrate has emerged, driving the development of silicon-based optoelectronics (SBO). SBO aims to explore the novel principles of micro-nano-scale photonic, electronic, and optoelectronic devices in different material systems, and use technologies and methods compatible with silicon IC process to heterogeneously integrate them on the same silicon sub- strate. It is a science and technology that forms a complete new large-scale optoelectronic integrated chip with comprehensive functions [10].

In the past few decades, SBO technology has made remarkable progress at both the device and system levels [11], [12], [13], [14], [15], [16], [17], [18], [19]. Several reviews offer comprehensive insights into the develop- ment of SBO [20], [21]. Currently, the focus of SBO is shifting towards achieving large-scale on-chip integration. However, this ambitious goal presents several technological challenges. These include balancing energy consumption and data rate in the context of large models like the AIGC, implementing efficient on-chip silicon-based light sources, and exploring the synergistic effects of photonic and electronic devices. To overcome these challenges, extensive research is being conducted on technologies such as silicon-based monolithic optoelectronic integration, ultra-low-loss passive devices, and silicon-based quantum dot

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laser growth. Prominent research groups such as Intel, Ayar labs, and John E. Bowers' team have proposed various solutions [13], [16], [19], and some research teams in China have also made significant contributions to the field [12], [15], [18].

The development of SBO began relatively late in China compared to other developed countries, starting in the early 2000s. In 2003, the Wuhan National Optoelectronics Laboratory was established with the support of the Chinese Ministry of Education, the Hubei provincial government, and the Wuhan municipal government. It focused on various disciplines such as basic photonics, integrated optoelectronics, micro-nano manufacturing, optical networks, communication, et al., and silicon-based optoelectronics is one of the most important research directions [22]. Huazhong University of Science and Technology formed a specialized research group dedicated to silicon-based optoelectronics and microsystems, in 2005. And in the same year, the Optics Valley of China (OVC) Optoelectronics International Symposium, a significant international conference on optoelectronics, took place in Wuhan [23]. Subsequently, Huazhong University of Science and Technology led a project named "Fundamental research on novel silicon- based micro/nano optoelectronic devices and integration tech- nology" in 2006 (973 grant 2006CB708310) [24]. In 2009, the Chinese Optics Letters published a special issue focusing on silicon-based optoelectronics [25]. The development of SBO continued in 2010 with International Workshop on Frontiers in Silicon Photonics held in Beijing, which discussed the future development direction for silicon-based optoelectronics over the next 20 years [26]. In 2011, Zhou established the first Silicon-Based Optoelectronics Technology and Application Summer School at Peking University which renowned as the "Huangpu Military Academy" of Silicon-Based Optoelec- tronics in China [27]. From 2011 to 2014, Peking University led a 863 project named "Silicon on chip 100 Gb/s coherent transceiver technology." The project successfully developed a 100 Gb/s silicon-based coherent optoelectronic transceiver chip in 2014, filling a gap in this field within China [28]. In 2012, Zhou published the first dedicated book on silicon-based optoelectronics in China [29], which was later followed by a second edition in 2021, showcasing the significant progress in this field [3]. These early events on SBO in China provide a glimpse of the first 10 years' development of silicon-based optoelectronics in China. Since 2005, China has played a significant role in driving the development of the global SBO field. Chinese scientists have increased their publications in SBO journals and conferences and strengthened their collabo- rations with foreign research institutions. In 2006, the Wuhan National Laboratory for Optoelectronics partnered with the Georgia Tech to provide an international platform for scholars worldwide to conduct SBO research [30]. Zhiping Zhou's team published important works early on, such as Ge-on-Si pho- todetectors, efficient grating couplers, and polarization beam splitters, taking the lead in SBO research in China [31], [32], [33]. Daoxin Dai's group at Zhejiang University initially focused on various passive devices and gradually shifted to the field of silicon-based optoelectronics [34], with their research on mode division multiplexing being particularly outstanding. In 2011, Dai collaborated with the John E. Bowers' team to propose a cascaded curved DC structure PBS with almost perfect performance, providing research ideas for a large number of polarization control devices in the future [35]. Other teams in China have also contributed a lot to SBO, but due to space limitations, we cannot list them all here.

China's focus on the development of SBO has grown significantly in recent years. It can be summarized as follows:

1) Started relatively late: began silicon photonics re- searches at the beginning of this century.
2) Academic research has rapidly caught up: many universities and research institutions have been engaged and produced world class achievements and publications [36], [37], [38], [39].
3) Process platforms have begun to take shape: a few pilot lines in China are up and running, more advanced production lines are in progress.
4) The commercialization of technological achievements is increasing: handful startups have been established and some large-scale companies are also strategically planning for this potentially very large market of silicon- based optoelectronics [40], [41], [42].
5) Increasing government support: strong support from both local and central governments has further bol- stered the development of silicon-based optoelectronics in China.

The above summarized the early history of SBO in China, and now provides a comprehensive overview of current status of SBO in China, including recent academic and industrial progress, to analyze the challenges and future development directions.

II. Academic Research Progress on Silicon-Based Optoelectronics in China

China has made significant advancements in silicon-based optoelectronics in recent years, driven by increased education, research and investment. Prominent universities, including Peking University (PKU), Zhejiang University (ZJU), Shang- hai Jiao Tong University (SJTU), Huazhong University of Science and Technology (HUST), have spearheaded education and research in this field. Notably, research institutions such as the Shanghai Institute of Optics and Mechanics (SIOM), Institute of Semiconductors (IOS), Institute of Physics (IOP), and Shanghai Institute of Microsystems and Information Tech- nology (SIMIT) of the Chinese Academy of Sciences have made remarkable research and development contributions as well. Some advancements and achievements are summarized as below.

A. Research Progress of Prominent Universities

PKU has been at the forefront of silicon-based optoelectronics research in China. In 2020, Zhou's team proposed a primary system for silicon-based optoelectronic computing [43], which is illustrated in Fig. 1. Collaborated with common microelectronic units, e.g., arithmetic and logic units (ALU), control units (CU), registers, and memories, the Optoelectronic Computing Unit (OECU) manipulated multidimensional information of light, such as wavelength, modes, phase, amplitude, and polarizations, to achieve efficient optoelectronic comput-

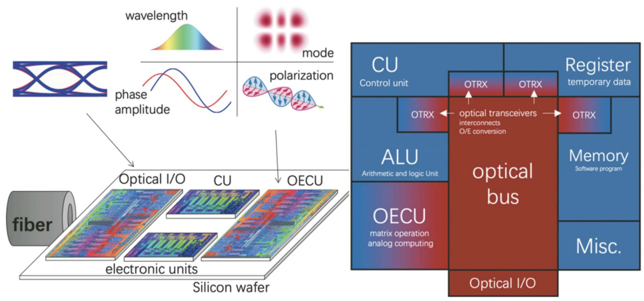


Fig. 1. Primary system for silicon-based optoelectronic computing.

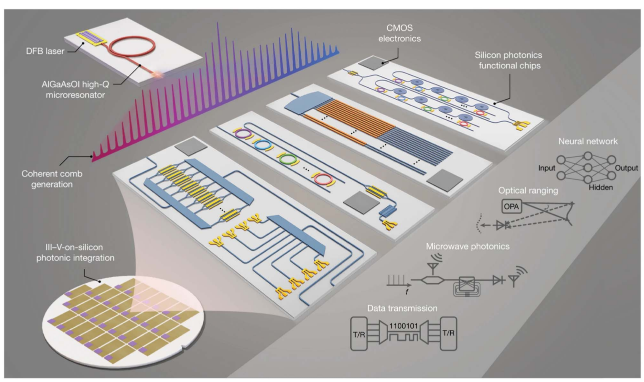


Fig. 2. Microcomb-based SiPh optoelectronic systems.

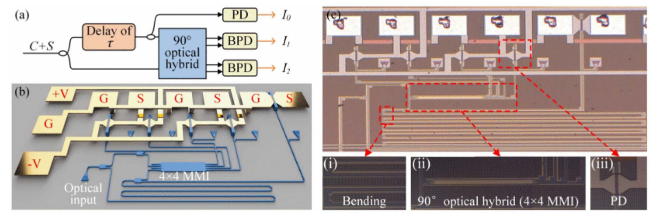


Fig. 3. Silicon photonic integrated direct detection receiver with highest electrical spectral efficiency.

ing which break through performance limits of the current microprocessor. The generated massive data will be handled by optical I/O for interconnects. The key to enhancing the overall performance of the computing system lies in leveraging the complementary advantages of optoelectronic and microelectronic computing, and establishing optoelectronic interconnections between internal and external units. This work elucidates the tendency of optoelectronic computing development that it cannot solely rely on combining binary electronic devices to accomplish intricate functions nor entirely replacing microelectronic computing with optical computing, but form a cohesive and complementary whole to transcend the performance limitations of existing microelectronic chips by the integration of photons, optoelectronics, and microelectronic devices on a common silicon-based chip platform through silicon-based integrated circuit technology. Apart from Zhou's work in silicon-based optoelectronic computing, another PKU research group led by Jianwei Wang, has made some contributions to the field of quantum computing [44], [45]. Their latest research work, titled "Very large scale integrated quantum graph photonics," has been published in the journal of Nature Photonics [45].

Chip-based light sources have long posed a challenge, limiting the potential applications of SBO technology. However, in 2022, Xingjun Wang's team made a significant breakthrough with their publication in Nature magazine titled "Microcomb driven silicon photonic systems." This research first reported a new type of SBO on-chip integrated system driven by an integrated microcavity comb in the world [18], as illustrated in Fig. 2. The team successfully achieved highly efficient and stable dark-pulse microcombs, driven by a direct on-chip laser pump. This advancement revolutionizes the integration of versatile SiPh engines with the microcombs, enabling a wide range of applications. Building upon this research, the team subsequently published other notable works. These included the development of a Microcomb-based integrated photonic processing unit and the implementation of microcomb-based parallel chaos for random number generation and optical decision making. Chao Xiang from the University of Hong Kong also made significant contributions towards achieving the monolithic integration of microcavity soliton frequency combs with lasers and amplifiers [13], [46]. In his latest work, he successfully provided an isolator-less ultra-low noise laser through 3D integration. This achievement allowed for the direct on-chip integration of III-V gain medium and ultra-low loss silicon nitride waveguides [13].

SJTU is another influential university in the field of silicon-based optoelectronics in China. In 2022, the team led by Yikai Su made significant strides in the development of SBO integrated direct detection receivers which was reported as an OFC post deadline presentation. As depicted in Fig. 3(a), one notable achievement was the implementation of a 35-GHz SiP carrier-assisted differential detection (CADD) receiver, enabling the demonstration of a 224-Gb/s OFDM 16-QAM signal transmission over an 80-km single mode fiber [47]. This transmission achieved a remarkable net capacity of 4.6 b/s/Hz ESE/# of pols, setting a new benchmark for integrated direct detection(DD) receivers. Fig. 3(b) is the 3D illustration of this SiP CADD receiver chip, and Fig. 3(c) is a micrograph of the integrated receiver chip. Notably, the micrograph insets (i-iii) provide magnified views of the bending, 90° optical hybrid (4×4 MMI), and photodiode (PD) components, respectively. A key advantage of their receiver is its local oscillator (LO)- free design, which holds potential for future cost-effective applications in passive optical networks (PON), data center interconnects, and mobile front-haul systems.

Silicon-based integrated LiDAR is the core technology for the next generation of autonomous driving. Weiqiang Xie 's work on heterogeneous phase shifts in 2019 is com- mendable for its high-speed performance and low power consumption [48]. Although China started relatively late in this field, recent investments in scientific research show a strong commitment to catching up and making progress. In 2022, Linjie Zhou's team presented a breakthrough in LiDAR technology by developing a LiDAR transmitter that combines a hybrid-integrated tunable external cavity laser and a high- resolution 2-D optical phased array beam-steerer [49]. This transmitter achieves a widely

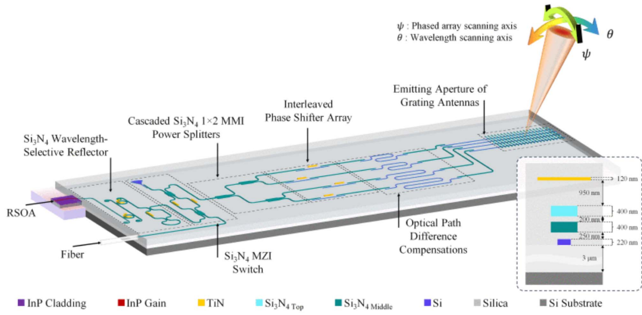


Fig. 4. Fully integrated solid-state LiDAR transmitter.

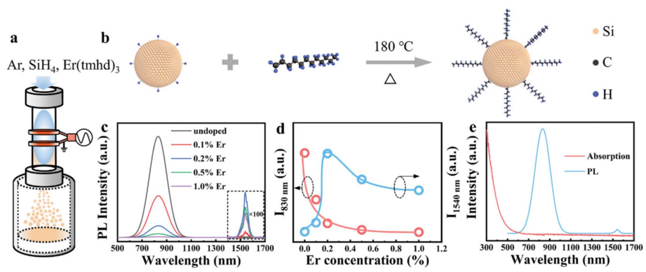


Fig. 5. Fabrication process and PL spectra of Er-hyperdoped silicon quantum dots.

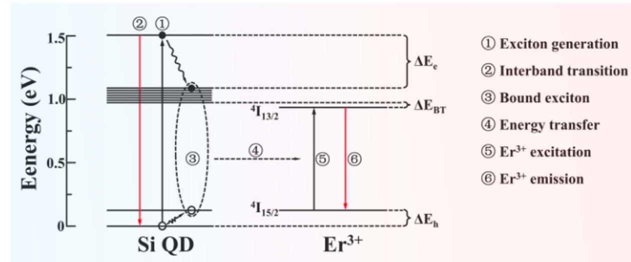
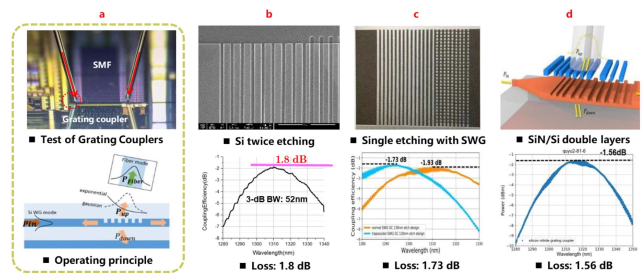


Fig. 6. Photoluminescence mechanism of Er-hyperdoped silicon quantum dots.



Coupling		Affiliation	Time	TE loss(dB)	3dB-BW	Si layer(nm)	Process	Reference
SMF	O - band	IME A*STAR's	2014	2.0	50nm	220	CMOS 180nm	Ruizhi Shi PTL
		Southampton Univ.	2017	1.9	47nm	220	EB	Chen Xia, OE
		Paris-Saclay Univ.	2016	2.5	44nm	220	EB	Daniel Benedikovic OE
		Zhejiang Univ.	2015	1.8	52nm	220	CMOS 180nm	unpublished
		Zhejiang Univ.	2021	1.73	46nm	220	EB	Under construction
		Zhejiang Univ.	2022	1.56	44nm	220	CMOS 140nm	Under construction

Fig. 7. Summary of high-efficiency O-band grating couplers.

tunable span of approximately 100 nm for single-mode lasing, with a side-mode-suppression- ratio of more than 42 dB, an output power of 18 mW, and a linewidth of 2.8 kHz. The device also demonstrates two- dimensional beam steering within a field-of-view of 140° × 16°, with a beam divergence of 0.051° × 0.016° measured at full width at half maximum. This beam-steering capability is enabled by leveraging the low propagation loss, negligible nonlinear loss, and low thermal sensitivity of silicon nitride, combined with the high mode confinement and efficient ther- mal tuning of silicon. The system architecture of the LiDAR transmitter is depicted in Fig. 4, representing the first successful integration of a LiDAR transmitter on the multi-layer silicon- nitride-on-silicon photonic platform. This achievement high- lights the potential of complementary integration in developing LiDAR transmitters with a sufficient optical power budget. Furthermore, this development opens the door for high-power on-chip lasing and low on-chip insertion loss.

Xiaodong Pi's team at ZJU has developed new near-infrared (NIR) emitters based on Erbium-hyperdoped silicon quantum dots [50]. The fabrication process and photoluminescence (PL) spectra of these Er-hyperdoped silicon quantum dots are shown in Fig. 5(a)–(e). The team has successfully synthesized free-standing Er-hyperdoped silicon quantum dots with Erbium concentrations of up to 1% using a nonthermal plasma method. It was found that the Erbium ions, with a valence of +3, are mainly located in the subsurface region of the Er-hyperdoped silicon quantum dots. These quantum dots emit NIR light at wavelengths of 830 nm and 1540 nm. Fig. 6 illustrates the photoluminescence mechanism of the Er-hyperdoped silicon quantum dots. These quantum dots have the potential to serve as a powerful platform for ratiometric NIR fluorescence. Additionally, they can be used to construct logic gates, enabling in-sensor computing. This research from ZJU opens up new possibilities for utilizing silicon-based quantum dots in the development of advanced optoelectronic devices and sensors.

Tao Chu from ZJU has made some contributions in the field of silicon-based passive devices, specifically in the area of high-efficiency O-band grating couplers [51], [52], [53], [54]. Fig. 7(a)–(e) provides an overview of the team's recent work on high- efficiency O-band grating couplers. Fig. 7(a) depicts the test diagram and working principle of the grating coupler, while Fig. 7(b)–(d) illustrate the structure and coupling efficiency test diagrams. These figures showcase the improvements made in the design and performance of the grating couplers. Fig. 7(e) provides a detailed performance comparison and process details. In their work in 2022, they achieved remarkable results using a 140 nm process node CMOS compatible process. The SiN/Si double-layer grating structure they developed exhibited a TE loss of only 1.56 dB and a 3 dB bandwidth of 44 nm. These researches demonstrate the advancements made by Tao Chu and his team in the development of high-performance and efficient O-band grating couplers.

Dai's team has made significant advancements in the field of mode division (de)multiplexers [35], [55], [56]. In their latest research, they proposed a 96-channel silicon-based reconfigurable optical add/drop multiplexer (ROADM), as depicted in Fig. 8. The ROADM comprises a six-channel mode/polarization demultiplexer and a 6×16 wavelength se- lector switch array based on micro ring resonator (MRR). By employing two

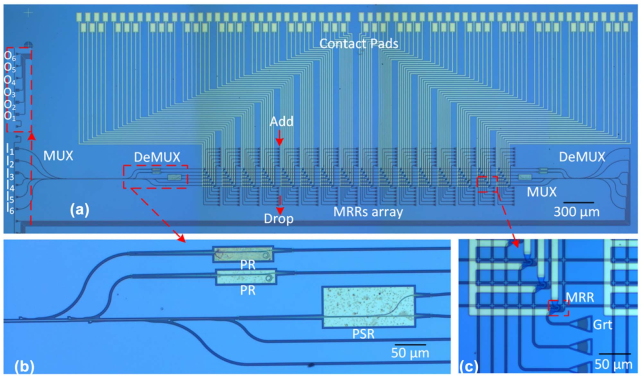


Fig. 8. Microscopy images of the fabricated ROADM for hybrid WDM-MDM-PDM systems.

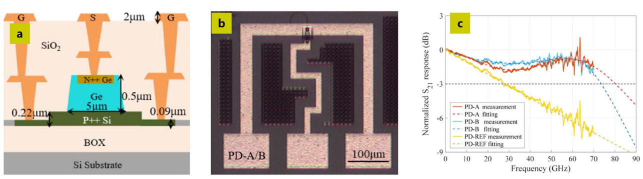


Fig. 9. 80 GHz germanium waveguide photodiode enabled by parasitic parameter engineering.

polarizations, three modes, and 16 wavelengths (1560–1590 nm), they achieved 96-channel multiplexing. Re- markably, the ROADM chip integrates 1000 components on a single chip, including 96 MRRs, 576 waveguide crossings, 192 grating couplers, 96 microheaters, 112 pads, 6 polarization separator rotators (PSRs), 4 asymmetric adiabatic couplers, and 4 asymmetric directional couplers. The channel loss ranges from 5 to 20 dB, inter-mode crosstalk is below −12 dB, and wavelength crosstalk is below −24 dB. This WDM-MDM- PDM hybrid multiplexing technique holds the potential to expand to a greater number of mode and wavelength channels, enabling ultra-high capacity data routing/switching. Conse- quently, it presents promising prospects for future optical interconnection networks.

Yu Yu and colleagues from HUST have made advancements in the development of the high-speed germanium waveguide photodiode. They proposed and investigated a technique to boost the bandwidth by engineering the parasitic parame- ters associated with the device. Through experimental in- vestigations, they successfully realize a bandwidth up to 80 GHz for vertical positive-intrinsic-negative (PIN) germanium photodiodes [57]. This bandwidth enhancement is achieved by optimizing the parasitic parameters comprehensively, without compromising the responsivity and dark current performance. This demonstrates the potential of parasitic parameter engi- neering as an effective approach to enhance the high-speed performance of germanium photodiodes. Fig. 9(a) illustrates the optimized structure of the p-i-n junction, while Fig. 9(b) shows the electrodes with optimal parasitic parameters. By implementing these optimized structures, Fig. 9(c) demonstrates a germanium-silicon waveguide photodiode with an improved bandwidth, increasing from 27 GHz to 80 GHz. What's more, this photodiode exhibits a low dark current of 6.4 nA and an optical responsivity of 0.89 A/W.

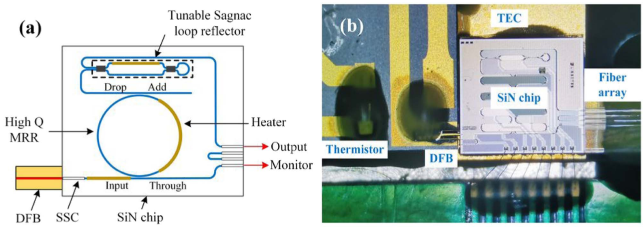


Fig. 10. Schematic diagram and microscope photo of the proposed hybrid integrated self-injection locked narrow-linewidth laser.

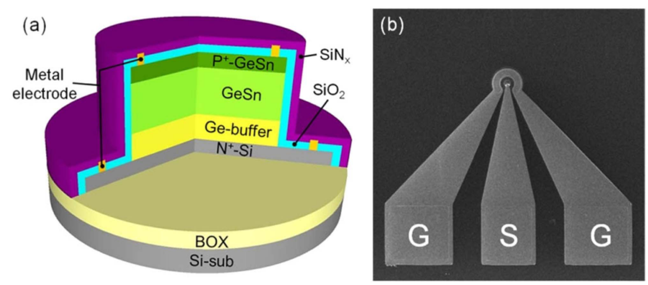


Fig. 11. Structure of the high-speed GeSn-on-Si photodetector at 2 um.

B. *Research Progress of Research Institutions*

SIOM is the oldest and largest laser science and technology institute in China, dedicated to using silicon-based optoelec-tronics platforms to realize the conversion of complex, large, high-power optical systems into low-power, high-stability, small-size chips. In 2022, Fang Wei's team at SIOM designed a hybrid integrated self-injection locking narrow linewidth laser based on a feedback-tunable silicon nitride microring resonator which realizes the miniaturization and integration of Narrow-linewidth lasers [58]. The laser's structure, depicted in Fig. 10, comprises a distributed feedback (DFB) semiconductor laser and a high-quality silicon nitride (SiN) external cavity. A variable Sagnac ring reflector is connected to the add- drop port of a high Q microring resonator (MRR), enabling flexible control of the ratio of feedback light and output light. By adjusting this ratio, the laser's intrinsic line width can be significantly reduced from 130 KHz to 345 Hz, with an impressive edge rejection ratio of 58 dB. This breakthrough holds significant practical applications, notably in the field of coherent laser confocal technology.

IOS of the Chinese Academy of Sciences is dedicated to researching new silicon-based Group IV semiconductor materials, devices, and related material physics. Their focus also includes developing high-performance infrared photode- tectors and silicon-based optoelectronic modules and chips specifically for data centers. In 2021, Liu et al. made a sig- nificant breakthrough by developing a high-speed GeSn-on-Si photodetector in the 2 um band [59], as illustrated in Fig. 11. The normal-incidence p-i-n structure photodetector was grown by MBE on SOI substrate with in situ thermal annealing and doping. This photodetector exhibits several advantages, such as low dark current, high responsiveness, and a wide operating bandwidth. At room temperature with a bias voltage of −1 V, the photodetector demonstrates a dark current density of approximately 125

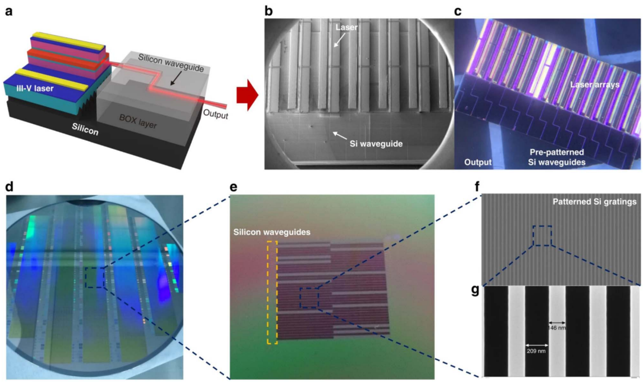


Fig. 12. Quantum dot laser on monolithic integrated silicon.

mA/cm^2 and a high optical responsivity of 14 mA/W at 2 um wavelength. Also, this work achieves a high 3-dB bandwidth (f 3 dB) of 30 GHz at -3 V bias. This performance is the highest one, among all reported III-V and IV photodetectors in the 2 um wavelength range. This work proves the potential of GeSn photodetectors for optical communication at the 2 um wavelength and opens up new possibilities in this spectral window.

IOP has been dedicated to the development of silicon- based on-chip light sources to facilitate large-scale silicon- based optoelectronic integration. They have made significant advancements in the field of silicon-based integrated lasers and are at the forefront of related research globally. In a recent progress in 2022, Ting Wang's group introduced the first quantum dot (QD) laser embedded on a Silicon-on-Insulator (SOI) substrate [59], as depicted in Fig. 12. The team achieved this by utilizing a pre-patterned grating structure and a mixed molecular beam epitaxy (MBE) epitaxy method to fabricate a high-performance embedded InAs QD laser with a single off- chip coupled silicon waveguide. The QD laser in this paper has the max continuous optical operating temperature of 85 °C, max output power of 6.8 mW, and coupling loss of 6.7 dB. This research holds significant value in providing a scalable and cost-effective epitaxy method. Moreover, it exhibits great potential for realizing all-monolithic silicon photonic inte- grated chips. Yating Wan's team has also done some excellent work in the field of quantum dot lasers, achieving coupling from quantum dot lasers to waveguides through evanescent wave. However, current progress has not achieved direct mea- surement of output power data from the output waveguide [60]. Some reviews have well summarized the current development status of on-chip lasers [61], [62], [63]. Monolithic integrated silicon- based lasers have the advantages of low power consumption and high integration, improving wall-plug efficiency is the focus of future development.

III. Industrial Development of Silicon-Based Optoelectronics in China

China's SBO industry has rapidly expanded in recent years, evident in the proliferation of domestic SBO platforms and companies. China now develops some platforms including

Fig. 13. CUMEC silicon-based optoelectronics platform.

Chongqing United Microelectronics' (CUMEC) SBO platform, Shanghai Industrial μTechnology Research Institute (SITRI)'s 180 nm 8-inch platform, and Institute of Microelectronics of the Chinese Academy of Science (IMECAS)'s

SiPh platform. In addition, there's been growth in the number of companies and diversification of SBO products. Today, China's SBO industry chain is gradually improving, with products extending from optical communication to various fields like communication, sensing, and computing. The in- formations of the above platforms and companies are outlined as below.

A. *Pilot Lines*

Established in October 2018, CUMEC is a rapidly expanding company in China's SBO industry. The company has a scale of about 3000 m^2 clean room, equipped with over 130 sets of process and measurement equipments, and a production capacity of 3000 pieces per month [64]. Fig. 13 is a picture of CUMEC's SBO platform. CUMEC launched its first SBO PDK CSIP180AL in May 2020 which was developed from the 180 nm silico-based optoelectronics process. By June 2021, CUMEC had released another three sets of process PDKs globally: the 130 nm complete SBO process PDK (CSIp130Cu), the 300 nm-thick silicon nitride photonics pro- cess PDK (CSiN300), and the 3D integrated process PDK (C3DS10), as shown in Fig. 14. CSiP130Cu is based on an 8-inch (200 mm) CMOS process and utilizes advanced 248 nm/193 nm DUV lithography technology to achieve 130 nm process nodes. CSiN300 is based on the 200 mm CMOS process to prepare low loss Si3N4 passive devices with a thickness of 300 nm. The loss of silicon nitride waveguide is less than 0.1 dB/cm, reaching the level of international mainstream process platforms. C3DS10 is based on an 8-inch heterogeneous integrated process, which can achieve 3D integrated manufacturing of 3D SiP or 3D SoC chips, as well as high-speed signal transmission silicon adapter board integrated packaging, reaching the international mainstream process level.

The SITRI 8-inch pilot line in China is focused on "More than Moore" technologies, specifically MEMS, silicon-based optoelectronics, piezoelectric, and biochips. It provides core process technologies and integration of new processes, mate-

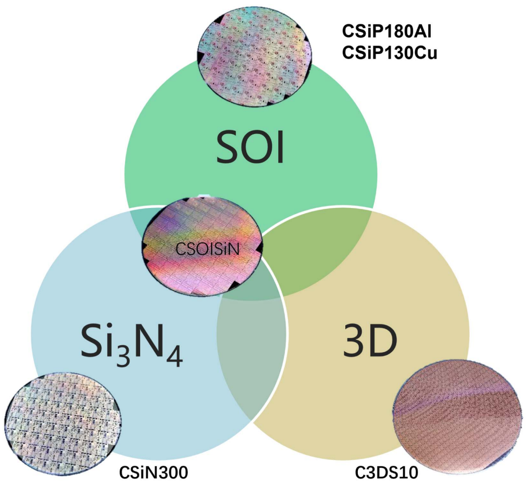


Fig. 14. CUMEC silicon-based optoelectronics process PDKs.

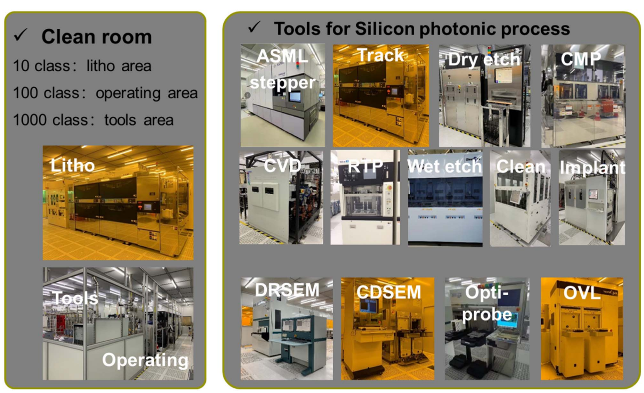


Fig. 15. SITRI 180 nm (90 nm) 8 inch platform.

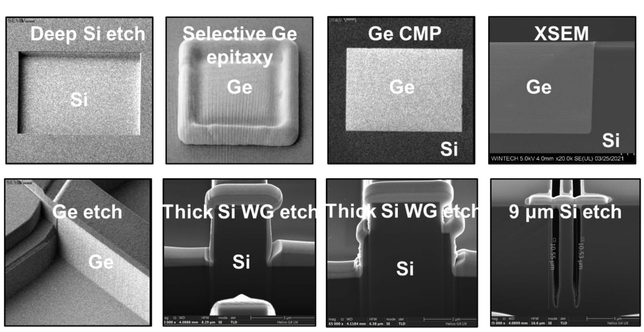


Fig. 16. SITRI integration process based on thick SOI.

rials, and devices. The platform has a scale of nearly 5000 m^2 and the SBO platform is biased towards CMOS front-end technology, with a mature process integration and a SBO device library [65]. It offers tools such as ASML stepper, dry etch, wet etch, and others, as shown in Fig. 15. As of November 2022, SITRI's 180 nm and 90 nm process are ready. SITRI's integration process, as depicted in Fig. 16, is based on the thick SOI platform, possesses lower transmission loss and higher process tolerance. The process flow based on the 3 um SOI

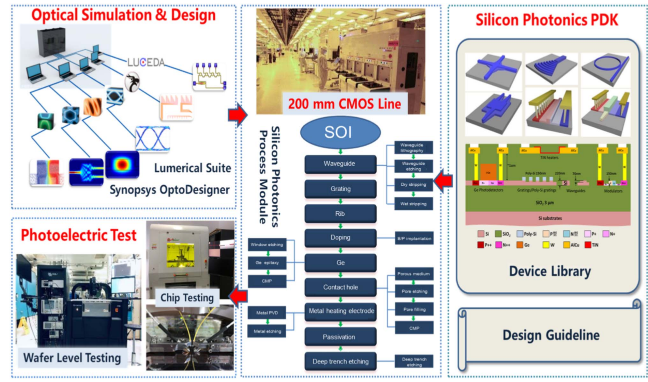


Fig. 17. IMECAS SiPh Platform.

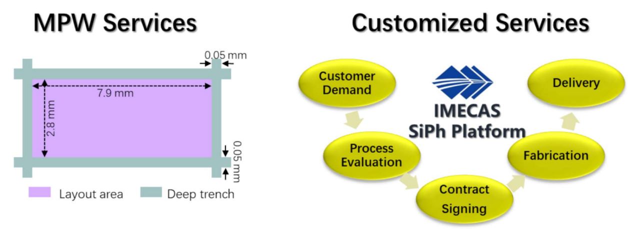


Fig. 18. IMECAS technical services.

platform is mature and can provide customers with one to one customized services.

IMECAS, boasting a comprehensive SBO process capability, also a leading player in China's SBO platform. Developed on an 8-inch pilot line [66], IMECAS has created a SBO process library and a basic device library. They have also established design rules and process specifications for SBO devices and chips, integrated with the software platforms of Synopsys OptoDesigner and Luceda Photonics IPKISS. In 2017, IMECAS released China's first silicon phtonics PDK, followed by PDK2.1 in 2022. Fig. 17 is the process flow diagram of IMECAS. IMECAS provides multi-project wafer (MPW) services and customized services, as shown in Fig. 18. The MPW service platform uses a 220 nm SOI substrate, with a block area of 7.9 mm $\times$ 2.8 mm and a minimum line width of 180 nm. Customized services include 220 nm SOI substrates, 3 um SOI substrates, quartz substrates, and low-loss silicon nitride waveguides based on silicon or SOI (180 nm DUV, 500 nm i-line, E-beam). The platform's key technologies include 220 nm/150 nm/70 nm passive device etching process, high-speed modulator doping process, TiN heater electrode process, germanium material epitaxy process, ohmic contact of silicon and germanium, and metal layer process. The IMECAS standard cell library includes passive devices like rectangular waveguide, ridge waveguide, MMI, Y-branch, optical crossover, AWG, grating coupler, etc. The active device achieves a 40 Gbps germanium detector and modulator, matching the performance level of international foundry platforms.

B. Corporations

The upstream of SBO industry chain mainly includes EPDA design tools, wafer, epitaxial, manufacturing equipment and other raw material suppliers. Midstream includes design, manufacturing and packaging vendors. The downstream includes the communication network equipment and other related equipment manufacturers. The SBO industry in China is currently lagging behind developed countries in terms of overall strength. In recent years, the industry chain has been improving, with representative Chinese corporations present in every link of the SBO industry chain. In the past, China did not attach much importance to the research and development of EPDA design tools, which put them far behind. However, in recent years, some domestic companies have emerged, such as LATITUDE and Max-Optics, developing their own simulation analysis software. Shanghai Simgui Technology is the only SOI material production base in China and a major global supplier. Wafer Works and Lion are reliable epitaxial suppliers, while Nata and Red Avenue are different material suppliers. Han's Laser and AMEC are prominent manufacturing equipment suppliers in China but still lags behind other foreign companies like ASML. CUMEC has played an important role in the midstream of the silicon-based optoelectronics and has experienced rapid development in recent years. Cylertech and Qxptech are also notable companies in the midstream of China's SBO industry chain. Downstream of the industrial chain, which may be the best link in China's SBO industry chain, with world-renowned enterprises such as Huawei, ZTE, and Accelink, et al. It's worth noting that some enterprises showcased impressive products at the recent 24th China International Optoelectronics Expo (CIOE). Accelink launched the 1.6T OSFP-XD DR8+ high-speed optical module [67], while H3C exhibited the 800G "LPO & liquid cooled" switch [68]. Driven by the large model, balancing transmission rate and power consumption is the most urgent challenge that needs to be solved. To address this, the co-packaged packaging (CPO) solution based on SBO technology remains the efficient approach for overcoming the bottleneck and reducing energy consumption and costs in the high computing power requirements of AI. Additionally, LPO technology can effectively reduce power consumption in cer- tain short-range scenarios. From the points mentioned above, it is evident that despite China's relative backwardness in the SBO industry, an increasing number of domestic companies are now entering the field and giving attention to every link of the industry chain. This indicates that the development of China's SBO industry will definitely go further.

IV. Conclusion

In the post Moore era, silicon-based optoelectronics has emerged as a crucial technology with significant application potential and has garnered considerable attention from both academic and industrial communities in China. This paper provides a review of the early development of SBO in China and presents the current status. Academically, Chinese universities and research institutions have made some progress in this field. The application of SBO in various fields such as computing, communication, sensing, and detection has been explored. It is worth noting that the research focus is gradually shifting from passive devices to active devices, such as light sources and photodetectors. The aim is to develop comprehensive and large-scale integrated silicon-based optoelectronic chips. On the enterprise front, China has developed some pilot lines. Platforms like CUMEC, SITRI, and IMECAS have significantly enhanced China's production and manufacturing capabilities of SBO applications. Furthermore, a growing number of local Chinese enterprises are entering various segments of the SBO industry chain, thereby improving the overall structure of the industry. Finally, despite some progress has made in silicon- based optoelectronics in recent years, China still lags behind developed countries in terms of semiconductor processing capabilities. To bridge this gap, greater investment from both the government and enterprises is required. These investments may be crucial for promoting the sustainable development of SBO in China.

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