Development and Thinking of Silicon Photonics Heterogenous Integration

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Abstract
Integrated photonics are fast-developing research field for next generation information technology. Current silicon photonic integrated chips strongly benefit from low-cost and high-density integration properties of existing CMOS technology. But limited by the physical properties of silicon, it is not a perfect material for different types of optoelectronic devices, such as laser sources, modulators, and infrared detectors. Therefore, heterogeneous integration is proposed by combining the advantages of CMOS process and superior opto-electric properties of heterogenous material systems, that can be an essential step towards next generation integrated optoelectronic chips. Here, this paper introduces the rapid progress of integrated photonics nationally and worldwide, while discusses the potential directions and opportunities in this field.

Keywords
photonic integration; silicon photonics; heterogenous integration

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1 Silicon photonics heterogeneous integration— the future of photonic integrated chips

The 21st century is an era of big data and cloud computing. For half a century, microelectronic technology has been developing rapidly in accordance with Moore’s law, and people have increasingly high requirements for information transmission and processing. With the development of information technology, the manufacturing processing for chips has advanced to the level of less than 10 nm, but the consequent problems of crosstalk, heating, and high power consumption become the bottleneck of microelectronic technology. The processing platforms of microelectronic chips in the post-Moore period can be divided into the more Moore platform of continuing to optimize the complementary metal-oxide-semiconductor (CMOS) process, the more than Moore platform of realizing system-in-package through advanced packaging technology, and the beyond CMOS platform of using new materials and devices. Different from the dependence of the more Moore platform on advanced semiconductor equipment and its requirement for huge investment, realizing optical interconnection between and within chips by the photonics heterogeneous integration technology can effectively solve problems in such aspects as bandwidth, power consumption, and delay of metal interconnection of microelectronic chips, which is an important extension of the existing microelectronic chips. Meanwhile, photonics heterogeneous integration of multiple materials can also produce a new generation information devices (such as photonic integrated chips) and is an important field of the information industry where more than Moore and beyond CMOS platforms can be realized.

Silicon photonic integration technology realizes the monolithic integration of optoelectronic devices and microelectronic devices by utilizing traditional microelectronic CMOS process, which is used to study and develop large-scale silicon-based integration with photon and electron as information carriers \cite{[1]}. Figure 1 is the concept diagram of a silicon photonic integrated chip, which is composed of light sources, modulators, optical waveguides, detectors, and circuit chips. Lasers generate optical signals, and modulators and detectors send and receive high-speed electrical signals and optical signals. At present, silicon photonic integration technology mainly relies on the manufacturing platform based on silicon-on-insulator (SOI) substrates and can realize the monolithic integration of detectors and modulators. However, limited by the photoelectric properties of silicon, there are still some problems in silicon photonic integrated chips, such as the failure to integrate light sources at a high density and integrate the low-loss high-speed optoelectronic modulators. Thus, silicon photonics heterogeneous integration technology, which gives full play to the superior photoelectric properties of different materials, has developed rapidly in recent years. It not only enables mass production of CMOS with silicon materials but also takes advantage of superior photoelectric properties of different materials, thus realizing indicators inaccessible to traditional silicon photonic integration technology. With the help of silicon photonics heterogeneous integration, a real monolithic silicon photonic integration system can be fabricated. This paper will briefly introduce the development status of this field in China and other countries and provides an outlook on its future development.
2 Silicon photonics heterogeneous integration platforms and development

2.1 Silicon photonics heterogeneous integration platforms

Unlike the microelectronics field facing the rapid development of integrated circuits, the optoelectronics field suffers many obstacles in integration. Since silicon photonic integration technology was first proposed by Soref [2] in the late 1980s, breakthroughs have been made in the performance, integrity, and application of devices. However, limited by the photoelectric properties of silicon, many manufacturers of mainstream optical modules still adopt the discrete package of optoelectronic devices. For example, the energy band structure of silicon with indirect band gap makes it unable to realize efficient on-chip light sources, and the Pockels effect limits the speed of modulators. Figure 2 lists current dominant optoelectronic devices of various material systems, such as laser light sources, single-photon sources, and modulators made from III-V materials, detectors made from Ge, modulators made from LiNbO₃, optoisolators made from the magneto-optic material YIG (yttrium iron garnet), modulators made from two-dimensional materials, and broad-spectrum low-loss optical waveguides made from SiN [3]. In particular, light sources made from III-V materials, detectors made from Ge, modulators made from LiNbO₃, and isolators made from YIG have incomparable advantages over silicon-based devices in optical communication applications. Therefore, to truly realize large-scale industrial applications of photonic integrated chips, we need to conduct the heterogeneous integration of silicon materials and different kinds of optoelectronic materials to give full play to the excellent characteristics of these materials.

Figure 1 Concept diagram of silicon photonic integrated chip

Figure 2 Schematic overview of multiple material systems and devices for silicon photonics heterogeneous integration

After years of efforts in research and development, silicon-based integration of various optoelectronic devices [such as silicon-based passive devices (waveguide, multiplexer, and demultiplexer), germanium/silicon detectors, and silicon modulators] has been realized in the field of silicon photonics, which, to a certain extent, can meet the application requirements of optical modules with rates below 400 Gbps [4]. However, as an insurmountable technical problem for silicon photonic chips, the light source must be heterogeneously integrated. Thus, this paper discusses the heterogeneous integration platforms for light sources. Figure 3 shows various platforms in the current silicon photonics heterogeneous integration field, with the integrity increasing and the technology maturity decreasing from left to right. ★ Chip-to-chip hybrid integration. Closest to lens coupling most extensively used in industrial applications, it is essentially a micropackaging technology, which requires plenty of time on the precise coupling alignment process in the coupling of multiple light sources and cannot realize the large-scale light source integration. Several optical module manufacturers adopt this technology to produce silicon photonics products. ★ On-chip hybrid integration by flip chip. The integration of prepared laser chips into silicon photonic chips by flip chip technology solves the problem of light source integration. However, silicon photonic chips need to be slotted by etching to accurately control the laser coupling height, and the high-precision coupling still needs to be fully realized, due to which this technology is not used in the industry. ★ On-chip heterogeneous integration by bonding. This technology was first proposed by the John Bowers research group in University of California, Santa Barbara (UCSB). It bonds III-V epitaxial materials to the prepared silicon photonic wafer and then manufactures III-V active devices by post-process. Although this technology can achieve large-scale integration of III-V materials and silicon photonic chips, it is difficult to develop, and the product yield

is hard to control. So far, only Intel has realized mass production by this platform. On-chip heterogeneous integration by direct growth. A slot is opened in the prepared silicon photonic wafer, and III-V materials are grown by selective area epitaxy. Then light sources are manufactured by III-V technology. This method is similar to the pilot production of heterogeneous integration by bonding and does not need complex die-to-wafer bonding process, which is a heterogeneous integration technology closest to the CMOS integration process. Despite its suitability for wafer-level mass production process, this technology has high material growth requirements for silicon-based III-V epitaxial technology and needs to solve such problems as the epitaxy of silicon-based heterogeneous materials, on-chip light source coupling, and on-chip light source aging. This technology is still in the academic research stage.

2.2 International research and development status

For nearly a decade, studies of the key materials and devices for silicon photonic integration have attracted extensive attention from scientific and industrial communities, with Intel alone spending billions of dollars on the research and development of silicon photonics. The Defense Advanced Research Projects Agency (DARPA) of the United States has set up the Lasers for Universal Microscale Optical Systems (LUMOS) project, in which 19 million dollars have been invested to research silicon-based heterogeneous material integrated light sources. The New Energy and Industrial Technology Development Organization of Japan has spent 2.25 billion yen on the development of silicon-based lasers with high brightness and high efficiency. The European Union has invested 2.62 million euros in “Horizon 2020” for the development of heterogeneous silicon-based light sources. Supported by governments, photonics heterogeneous integration technology is advancing rapidly and has made many breakthroughs in academic and industrial fields.

(1) Academic research. Research institutions represented by the University of California and Ghent University have developed silicon-based lasers with heterogeneous integrated quantum well materials through heterogeneous integration by bonding [5,6]. Harvard University has achieved high-speed modulators with LiNbO₃ silicon-based bonding [7]. Hewlett-Packard has manufactured silicon-based lasers, microring modulators, and detectors by bonding quantum dot materials [8]. The University of California and the Technical University of Denmark have achieved optical frequency combs by bonding AlGaAs [9,10]. Swiss Federal Institute of Technology in Lausanne (EPFL), the California Institute of Technology, and the University of California have developed optical frequency comb devices through the SiN platform [11]. NTT has realized a laser with the direct modulation bandwidth of 108 GHz by bonding InP to SiC substrates and developing thin film lasers heterogeneously integrated through growth, which breaks the world record [12]. Studies of heterogeneous integration through direct growth in recent years mainly involve silicon-based light sources developed using the technology of silicon-based direct epitaxial growth of quantum dots by such units as the University College London and the University of California, such as silicon-based quantum dot microring lasers, mode-locked lasers, DFB lasers, and tunable lasers [13,14].

(2) Industry. Luxtera, Rockley Photonics, and Skorpio have displayed products by chip-to-chip hybrid integration, on-chip hybrid integration by flip chip, and on-chip heterogeneous integration, respectively. Intel developed 100 Gbps four-channel silicon photonic modules through on-chip heterogeneous integration by bonding in 2016 and has sold more than 5 million modules by 2021, making it the only company in the world that achieves mass production by heterogeneous integration. Meanwhile, Intel is also deploying the silicon-based quantum dot laser technology for heterogeneous integration through direct growth. Besides, semiconductor foundries such as Global Foundries, STMicroelectronics, Tower Jazz, and Taiwan Semiconductor Manufacturing Company have their own silicon photonics production lines. Global Foundries has shown its hybrid integration technology using on-chip flip chip, and Tower Jazz, working with Quintessent engaged in the development of quantum dot lasers based on direct growth, plans to develop the silicon photonics process with direct growth-based heterogeneous integration technology.

2.3 Research and development progress in China

Under the support of “863 Program”, “973 Program”, National Natural Science Foundation, and other projects, China has also made more efforts in the research of silicon heterogeneous integration and has achieved major outcomes in key silicon photonic integrated devices in recent years. Discrete devices such as modulators, detectors, multiplexers, and demultiplexers have been successfully developed, and great progress has been made in substrates, light sources, and high-speed optoelectronic modulators for heterogeneous integration.

Figure 3 Silicon photonics heterogeneous integration platforms
(1) Academic research. On-chip heterogeneous integration by direct growth. Institute of Physics, Chinese Academy of Sciences (CAS) has effectively solved the problem of heteroepitaxial growth of III-V materials on silicon by utilizing the homoepitaxial and heteroepitaxial growth on patterned silicon substrates, achieving high-quality silicon-based on-chip light sources [15-17]. On-chip heterogeneous integration by bonding. Shanghai Institute of Microsystem and Information Technology, CAS has developed silicon heterogeneous integration substrates of multiple materials by ion implantation and exfoliation, including SiCOI, LNOI, and III-V OI, providing a material platform for silicon photonics heterogeneous integration of multiple materials [2, 3]. Units such as Peking University, and Institute of Semiconductors, CAS have developed mW-level silicon-based lasers with transparent conducting electrodes [18], Chip-to-chip hybrid integration. Shanghai Jiao Tong University, Tsinghua University, and National Optoelectronics Innovation Center have developed narrow-linewidth tunable lasers [19-21], Silicon photonics heterogeneous integration of new materials. Units such as Sun Yat-Sen University, Huazhong University of Science and Technology, and Zhejiang University have developed high-performance optoelectronic modulators, polarization controllers, etc. by silicon-based LiNbO$_3$ film [22-24]. Units such as Peking University, Zhejiang University, and Nanjing University have attempted silicon-based luminescence through rare earth doping [25, 26], Institute of Semiconductors, CAS and Xiamen University have tried light source devices by using germanium/silicon materials heterogeneously grown on silicon-based substrate [27]. Zhejiang University has produced a number of devices in integrated photonics with silicon-based chalcogenides and two-dimensional materials, extending silicon-based optoelectronic devices to the middle-infrared band [28, 29].

(2) Industry. Most Chinese optical module companies adopt traditional lens packaging technology, and none uses the heterogeneous integration solution for mass production. Compared with the industrialization development of companies and foundries in other countries, that in China is slow in silicon heterogeneous integration, and there are not many companies developing products with heterogeneous integration technology and delivering them in batches. Heterogeneous integration materials. Silicon-based LiNbO$_3$ materials manufactured by Jinan Jingzheng Electronics Co., Ltd. is dominant, making the company the material supplier of almost all thin-film LiNbO$_3$ modulators in China and other countries. Devices made with heterogeneous integration materials. A number of start-ups incubated from schools and research institutes have emerged, such as Liobate Technologies Limited manufacturing thin-film LiNbO$_3$ modulators and Heterosemi producing silicon-based heteroepitaxial materials and light sources. Heterogeneous integration modules. Irixi has delivered dense-wave 10-channel 100 Gbps modules in small batches based on chip-to-chip hybrid integration. Hisense Broadband Multimedia Technologies Co., Ltd. has tried product development with bonding integration technology, but has not released any product yet.

(3) Silicon photonic chip manufacturing platforms. In recent years, China has gradually increased input to integrate with advanced silicon photonics research platforms of other countries, such as Interuniversity Microelectronics Centre (IMEC) and Institute of Microelectronics (IME), Agency for Science, Technology and Research in processing lines. Units such as United Microelectronics Center, Institute of Microelectronics, CAS, and Shanghai Industrial Technology Research Institute have established their own silicon photonics processing lines. At the same time, Institute of Microelectronics, CAS and United Microelectronics Center have also developed optoelectronic simulation software for design, making an arrangement from the software design side. However, optical module manufacturers in China still select overseas foundries for the pilot production of silicon photonic chips. In terms of heterogeneous integration, the SiN pilot production of United Microelectronics Center has been open to the public, while no heterogeneous integration technology of light sources has been open in China.

3 Development trend and thinking of silicon photonics heterogeneous integration

3.1 Multiple optoelectronic materials and silicon heterogeneous integration

Silicon photonics heterogeneous integration is gradually developing from heterogeneous integration of III-V materials and silicon to that of multiple materials and silicon, and materials such as SiN and LiNbO$_3$ have also become the main materials of silicon heterogeneous integration. For the sake of making the most of the photoelectric properties of different materials, there are even photonic chips made by simultaneous heterogeneous integration of multiple materials on a silicon substrate, such as ultra-narrow-linewidth silicon-based lasers made by heterogeneous integration of InP quantum well materials, SiN, and SOI materials and heterogeneously integrated silicon-based soliton optical frequency combs realized by this platform. As the bonding platform gradually becomes mature, the heterogeneous integration of multiple materials and silicon substrates, which gives full play to superior photoelectric properties of different materials, will become a mainstream direction of future development.
3.2 Development of silicon photonics heterogeneous integration platforms to higher integrity

In terms of heterogeneous integration platforms, silicon photonics heterogeneous integration is developing from chip-to-chip and on-chip hybrid integration to on-chip heterogeneous integration by bonding and by direct growth. We compare the above four heterogeneous integration platforms from the perspectives of integrity, production efficiency, and technology maturity (Table 1). Chip-to-chip hybrid integration. Limited by hybrid integration between two chips, this technology cannot realize wafer-level production, and integrity and production efficiency are restricted. On-chip hybrid integration by flip chip. This technology can realize wafer-level integration on condition that lasers and silicon photonic wafer devices used for heterogeneous integration should be specially designed. For example, special structures and waveguide coupling structures for height alignment are made on silicon photonic wafers, and the planarization process of lasers is used for flip chip. These special processes will affect the product yield and are thus the difficulties in the development of this platform. Moreover, chip-to-chip hybrid integration and on-chip hybrid integration by flip chip both rely on high-precision packaging equipment and require the mechanical alignment accuracy of equipment to reach the 0.5 µm level, which results in increased time consumption in high-precision packaging alignment and thus low production efficiency. At present, commercial applications of photonic heterogeneous integration are still restricted to chip-to-chip and on-chip hybrid integration solutions. On-chip heterogeneous integration solutions with high integrity and production efficiency are the future development direction of photonic heterogeneous integration. Nevertheless, heterogeneous integration by bonding or direct growth requires the organic combination of the traditional CMOS processing line and heterogeneous material processing line. On-chip heterogeneous integration by bonding. At present, only Intel has achieved the productization of the on-chip heterogeneous integration by bonding by using its original CMOS production line and III-V compound semiconductor production line. Although only Intel has realized mass production by this platform, several other companies (such as Hewlett-Packard and Skorpios) have deployed it, expecting to develop it into a mainstream platform with high density for heterogeneous integration of multiple materials in a short time. On-chip heterogeneous integration by direct growth. This platform is of great development potential, and, if the problems of optical coupling in heterogeneous integration and heterogeneous selective area epitaxial growth can be solved, will become a heterogeneous integration platform that is closest to the traditional CMOS process, which is an ideal solution to silicon photonics heterogeneous integration. However, we still need to conduct scientific research to further improve its technology maturity, and thus it is also a key direction of silicon photonics heterogeneous integration requiring increased research input.

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<tr>
<th>Platform</th>
<th>Integrity</th>
<th>Chip production efficiency</th>
<th>Technology maturity</th>
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<tr>
<td>Chip-to-chip hybrid integration</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>On-chip hybrid integration by flip chip</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>On-chip heterogeneous integration by bonding</td>
<td>Less high</td>
<td>Moderate</td>
<td>Moderate</td>
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<tr>
<td>On-chip heterogeneous integration by direct growth (monolithic integration)</td>
<td>High</td>
<td>High</td>
<td>Low</td>
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3.3 Advancement of silicon heterogeneous integration from research and development to applications

With the advent of such technology nodes as chip-to-chip optical interconnection and co-package, silicon photonics heterogeneous integration technology will become an important platform in the photonic integration field in the post-800 Gbps era. Since the existing modular solutions cannot support the future data interconnection requirement for large broadband, low power consumption, and integration, the integration development of optical chips will be boosted, which will further promote the industrialization of chips based on silicon photonics heterogeneous integration. With the heterogeneous integration of multiple material systems and silicon substrates, the applications have expanded from traditional data communication and telecommunication optical interconnection to other fields. For instance, solutions based on silicon heterogeneous integration have also emerged in such fields as biosensing, laser radar, optical computing, and light quantum.

There are still few companies engaged in silicon photonics heterogeneous integration in China because traditional optical communication companies generally sit on the fence about this new platform due to high technical threshold. In addition, this technology requires large commercial input. It is necessary to design and build production lines integrating heterogeneous materials and traditional silicon-based CMOS wafers, which requires extremely high capital investment and large market demands. However, the existing optical communication market demand cannot provide enough support to establish a commercial 12-inch silicon photonics production line for silicon photonics heterogeneous integration with compound semiconductors, due to which few companies in China and even the world conduct the industrialization of this technology. Intel reduces production costs with its own traditional CMOS production line and conducts years of technical development, becoming the only company realizing...
mass delivery of 100 Gbps optical modules from the data center by using silicon photonics heterogeneous integration. The real purpose of developing this technology is to provide technical reserves for more than Moore and beyond CMOS platforms, so as to realize the on-chip optical interconnection of their processors and lead the technologies for photonic integrated chips in the future. Apple Inc. intends to adopt silicon photonics heterogeneous integration technology in its next generation Apple Watch, expecting to expand silicon photonics heterogeneous integration to the consumer electronics market. In view of the international research, development, and industrialization of silicon photonics heterogeneous integration, there is an urgent need for China to speed up the advancement from research and development to applications and industrialization in this field.

In brief, from the predictable optical communication applications to consumer sensing applications and the future optical computing and optical quantum applications, the market demand for silicon photonics heterogeneous integration is just getting started with vast potential for future development. However, only a few companies in China, such as Huawei, Accelink, and SiFotonics, are actively involved in the silicon photonics field without starting the industrialization of silicon photonics heterogeneous integration. Although China has reached international advanced levels in some segments of silicon heterogeneous integration, it is still weak in the industrialization of silicon photonics heterogeneous integration. It is suggested that a silicon photonics heterogeneous integration research center be built, and multiple silicon photonics research and development production lines invested by the nation with the center and distinctive research institutes in different fields to explore the CMOS compatible semiconductor processing mode of silicon photonics heterogeneous integration, so as to accelerate industrialization.

Compared with the microelectronics industry, the optoelectronic field in China has some technical reserves reaching world-class levels, which makes China able to keep abreast of and even lead the world in the chip field. Silicon photonics heterogeneous integration, as an important technology for the future development of photonics, needs strong support from the nation and the close combination of the enterprises, universities, and research institutes, thus promoting China to lead the world in the future integrated photonics field.

References


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