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ABSTRACT

The huge development of micro-/nano-manufacturing techniques on different materials has greatly expanded the possibilities of realizing on-chip multifunctional devices on photonic integrated circuits. In recent years, we have witnessed technological advancements, such as active photonic applications through hybrid integration. In this Perspective, we first summarize the integrated photonic materials, hybrid integration technologies, and corresponding coupling techniques in hybrid integration and give the technique prospects. We also introduce significant advances in hybrid integration technologies for active photonic applications, such as laser sources, optical frequency combs, and modulators, and give our views that are likely to develop rapidly. Finally, we discuss the challenges in hybrid technologies and photonic applications.

I. INTRODUCTION

In recent decades, the rapid development of modern information technologies, particularly in smartphones, large-scale computing, and the global internet, has greatly propelled the advancement of the micro-/nano-fabrication technology. This progress has not only paved the way for the growth of traditional integrated electronics but also fostered the flourishing of modern integrated photonic technologies,[1] especially mature silicon photonic technologies,[2] which directly benefit from complementary metal-oxide semiconductor (CMOS) advanced integration technologies. However, the monolithic silicon photonic integration is limited as a platform for passive devices,[3] which makes it hard to satisfy the integration for both active and passive multifunction devices.

As a consequence, it is noticed that the field of integrated photonics is increasingly moving toward the integration with multiple materials, such as silicon nitride (SiN),[4] lithium niobate (LN),[5] III–V materials,[6,7] aluminum nitride (AlN),[8] silicon carbide (SiC),[9] rare-earth (RE) ion-doped materials,[10,11] two-dimensional (2D) materials,[12] quantum dots (QDs),[13,14] and many others, which aims to break through the limitations of traditional single-material systems of integrated photonics. It is a greatly inspiring and exciting trend since it has sparked rapid development in active photonics, leading to the emergence of numerous remarkable on-chip active device solutions, such as efficient laser sources,[15,16] frequency comb sources,[17] high-performance modulators,[18] microwave photonic (MWP) filter,[19] and photodetectors.[20–27]

To achieve the integration with multiple materials, hybrid integration and heterogeneous integration[28–30] are the two main options. Without loss of generality, hybrid represents a "weak" form of multi-material integration that relies only on single-material-based processes. Differently, heterogeneous represents a "strong" form of multi-material integration, typically involving the composite processing of multiple materials; that is to say, the heterogeneous

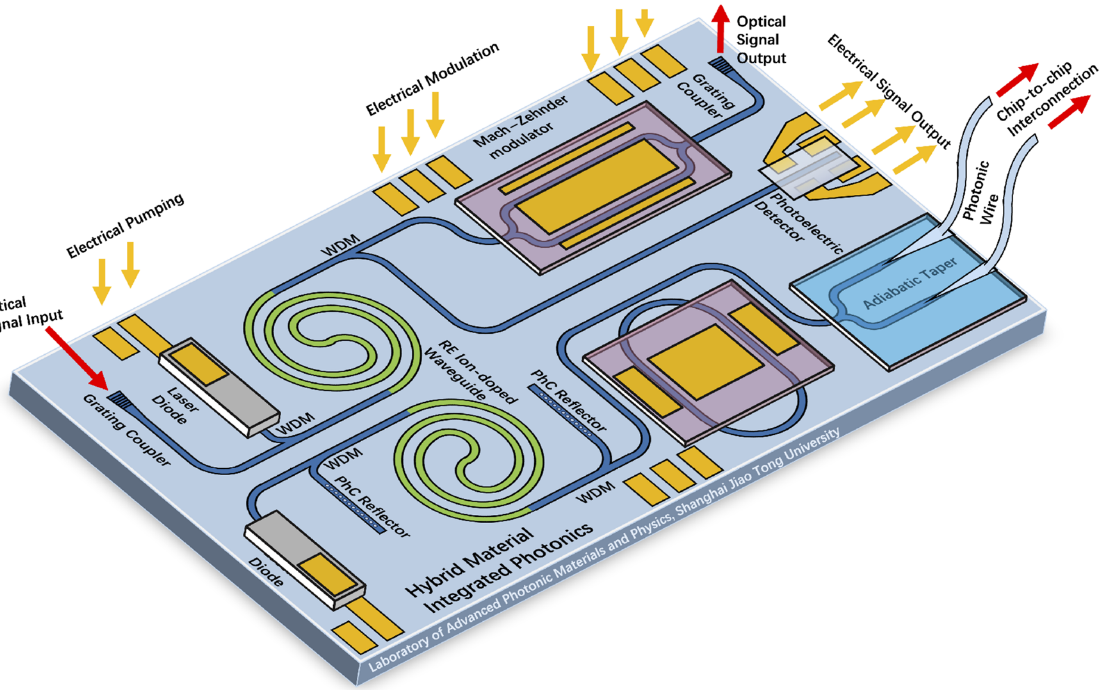

FIG. 1. Multifunctional hybrid material photonic integrated circuits.

integration processes require combining and etching more than one material in a single chip. The concepts of these two integration methods can also directly reflect the advantages and disadvantages of each. Although hybrid integration is a "weak" integration of materials, it may bring about issues such as relatively high losses. However, its advantage lies in relying solely on single-material-based technologies that have been widely studied in the past few decades, without exploring the sophisticated processes of multi-material systems anew. "Start with the ABCs." We believe that the hybrid integration technology, which can host a wide variety of active and passive photonic devices, as illustrated in Fig. 1, will be a more practical and promising research direction in the near future, serving as a stepping stone in the field of multi-material integrated photonics.

Therefore, we have summarized the development of hybrid integration technologies in Sec. II and advances in achieving active photonic applications through hybrid integration in Sec. III. The challenges and perspectives for hybrid material integration are given in Sec. IV, which may benefit researchers in integrated photonics.

II. HYBRID MATERIAL INTEGRATION

Thanks to the development of micro-/nano-fabrication technologies and materials science in the past two decades, hybrid materials integration has shown increasingly significant advantages in the field of integrated photonics. In this section, we will introduce the common and novel materials used in integrated photonics. Then, we will also introduce the process of hybrid material integration and the coupling methods demanded for achieving hybrid integration.

A. Materials for integrated photonics

In the past few decades, there are many extensive explorations and developments in integrated photonics for various material systems, such as silicon (Si), silicon nitride (SiN), lithium niobate (LN), III–V semiconductors, aluminum nitride (AlN), silicon carbide (SiC), and so on. These diverse material platforms show unique properties and significant advantages and potential in respective fields or applications. We list some common physical parameters of these optical materials in Table I. We will provide a brief overview of advantages of each commonly used materials in integrated photonics.

When it comes to integration photonics, especially the optical communication technology, silicon photonics is undoubtedly a fascinating field. Silicon and silica, which constitute the silicon-on-insulator (SOI) platform,[3,42,43] are the key materials in silicon photonics. The SOI platform has many unique advantages. The most important one is it uses mature standard CMOS processes, which are commonly used in electronic semiconductor industry. It provides typically cost-efficiency, high integration density, superior compatibility, and excellent production yields for SOI devices. These distinctive benefits of SOI, surpassing alternative materials, have laid the groundwork for the recent advent of intricately complex photonic integrated circuits, such as massively scalable frequency comb-driven integrated photonic systems,[44,45]

TABLE I. List of key properties of some common materials in integrated photonics (thin film).[a,b,c]

Material	Refractive index	Transparent window (μm)	Waveguide propagation loss (dB/cm)	Thermo-optic coefficient (10^{-5} K^{-1})	Second-order nonlinear coefficient (pm/V)	Nonlinear refractive index (n_2: 10^{-19} m^2/W)	EO coefficient (pm/V)
Si	3.48[31]	1.1–5.5[32]	0.027[33]	18[8]	...	40[8]	...
SiN	2.00[31]	0.25–8.3[28,34]	0.000 34[35]	2.5[8]	...	2.4[8]	...
LN	2.21(o) 2.14(e)[31]	0.35–5.5[32]	0.003 4[36]	0.2(o) 3.3(e)[8]	$d_{31} = -4.3$ $d_{33} = -27.0$ $d_{22} = 2.1$[31]	1.8[31]	$r_{13} = 0.6$ $r_{22} = 6.8$ $r_{33} = 30.9$ $r_{51} = 32.6$[31]
InP	3.17[28]	0.93–15[28,37]	<0.5[28]	19.4[28]	...	140[38]	...
GaAs	3.38[31]	0.9–17.3[32]	0.4[32]	23[8]	$d_{36} = 170$[31]	260[8]	$r_{41} = 1.43$[31]
AlN	2.12(o) 2.16(e)[31]	0.21–11[28,39]	0.14[40]	2.3(o)[8]	$d_{31} = 1.6$ $d_{33} = 4.7$[31]	3.5[8]	$r_{13} = 0.67$ $r_{31} = -0.59$[31]
SiC	2.3–3.2[32]	0.37–5.6[32]	0.15[32]	0.015[41]	$d_{33} = -13$ to -24[32]	6–8[32]	$r_{33} = 1.8$[32]

[a]All superscripts in Table I represent citations, not exponents.
[b]The values in Table I are sourced from the referenced articles, and the actual conditions for obtaining those values are based on the content in the corresponding references.
[c]"..." represents that we have not found any specific data for reference to the best of our knowledge.

very-large-scale integrated quantum photonics,[46] sophisticated integrated silicon photonic micro-electro-mechanical systems (MEMS),[47] and high-bandwidth modulators.[48]

Long time ago, passive devices, including low-loss waveguides and high-Q microcavities,[49] as well as active devices, including pn junction-based modulators,[50,51] and photodetectors based on thin film germanium grown by molecular beam epitaxy on silicon,[52] have already been realized on the SOI platform. Although state-of-the-art SOI waveguides have achieved propagation losses as low as 0.027 dB/cm,[33] with a general benchmark of around 0.1 dB/cm,[53,54] their application in integrated photonics is limited due to the high nonlinear losses caused by two-photon absorption (TPA)[55] in silicon. Moreover, the indirect bandgap of silicon,[28,56,57] which causes low light-emitting efficiency, makes it difficult to achieve light sources on the SOI platform. Meanwhile, many integration technologies, such as die-to-wafer bonding, wafer-to-wafer bonding, and direct grow technique,[29] are developed increasingly in silicon photonics. This benefits a lot for hybrid integration and heterogeneous integration.

SiN is also a widely deployed photonic material, which has wide availability in CMOS electronic integrated circuit technologies.[4,58–60] Compared to SOI, SiN can achieve more highly confined and lower mode volume integrated optical waveguides due to its lack of nonlinear losses caused by two-photon absorption. Liu *et al.* demonstrated that the loss of SiN waveguide can be as low as 0.034 dB/m, which can directly stimulate Brillouin scattering (SBS) laser.[35] SiN has also been developed for various applications in the field of integrated photonics, such as on-chip nonlinear generation[61] and on-chip soliton microcomb generation.[62] In addition, various hybrid and heterogeneous material integration technologies, such as photonic Damascene process[63–66] and III–V semiconductor hybrid integration,[67] have been developed based on the SiN platform. Although certain stages of these processes do not satisfy CMOS compatibility, they enable the fabrication of composite material systems, which constitute many kinds of optical materials, such as lithium niobate.[16] In a certain sense, SiN can be seen as a "patch" or alternative to SOI, making silicon photonics broader development prospects.

In the field of integrated photonics, another impressive material platform is LN.[5,31,68] Due to its low loss,[36] rich nonlinear optical effects,[69–71] and ability to achieve large bandwidth electro-optic modulation, LN is praised as the "silicon of photonics."[72] The vibrant development of LN in integrated photonics is mainly attributed to the mature production of high-quality thin film lithium niobate (TFLN) wafer benefiting from the commercialization of the "smart-cut" process[73,74] around the 2010s. Since then, many works on the TFLN platform have been reported, such as integrated optical waveguides with losses as low as 0.0034 dB/cm,[36,75,76] ultra-high bandwidth (electro-optic bandwidth >100 GHz), and ultra-high modulation efficiency ($V_\pi \cdot L = 2.2$ V cm).[77] Additionally, LN also exhibits high piezoelectric coefficients and low acoustic propagation losses.[78] Based on the electro-optic and piezoelectric effects of LN, highly efficient microwave-to-optical conversion can be achieved.[79] It also has research potential in the future development of quantum computing.[80,81] Although the cost of fabrication of LN devices is relatively high, caused by the CMOS-incompatibility of LN, and due to the requirements of expensive and specialized plasma etching equipment,[82] there is an alternative of direct etching of LN, while sacrificing some advantages of the TFLN waveguides, which is hybrid or heterogeneous integration to form strip-loading or strip-loading-like waveguides, such as LN–SiN,[16] LN–chalcogenide glasses (ChGs),[83] and LN-on-Sapphire.[84] Additionally, the ferroelectric material lithium tantalite (LT), akin to the characteristics of LN, exhibits a higher tolerance for optical damage,[85] an extended ultraviolet cutoff wavelength,[86] reduced birefringence, and high piezoelectric coefficients.[31] In particular, electro-optic modulators[87] utilizing LT have shown considerable promising development for future research endeavors, such as broadband electro-optic frequency comb generation.

Decades ago, people turned their attention to III–V materials, such as InP,[88] GaAs/AlGaAs,[89] and GaN,[90] in order to solve the problem of which it is hard to achieve an on-chip light source in a silicon-based material platform. III–V materials are important semiconductor materials whose losses are relatively lower compared to the silicon-based material platform. More importantly, people can construct the stacked structure with different doped III–V materials, such as quantum well (QW),[91,92] to build an artificial energy band structure so that it can achieve controllable light emission, modulation, and absorption. However, III–V materials also have some technical shortages, such as high manufacturing costs due to the sophisticated process of multiple materials integration. For example, more improvements in the fabrication process are required due to the thermal stress caused by different materials.[7] Despite that, III–V is currently one of the most mature material platforms in both academia and industry. It shows wide application prospects in the future of hybrid material integration and heterogeneous integration. By integrating III–V materials with silicon[6] and SiN,[93] high-performance and low-cost photonic devices, such as optical modulators, lasers, and detectors, can be achieved.

AlN is a material with noteworthy optical properties. It has a width transparent window, especially with low losses in the visible and ultraviolet (UV) wavelength range.[94] It also exhibits excellent electro-optic, acousto-optic, and piezoelectric properties,[8] making it potentially valuable in fields of electro-optic modulation,[95] acousto-optic modulation,[96] and UV nonlinearity.[97] Additionally, it has high thermal conductivity, a small thermo-optic coefficient, and low spontaneous fluorescence, making it advantageous for thermal stability in optical devices. However, a drawback of AlN materials is its relatively high production cost. Nevertheless, AlN remains a promising material in the field of multiple physics coupling systems, such as on-chip piezo-optomechanics,[98] which is an urgent demand for the development of the technologies of hybrid integration and heterogeneous integration.

SiC[9] has been a relatively new material platform in recent years. A chip-scale low-loss SiC waveguide, which is nearly 0.3 dB/cm,[99] and an ultra-high Q resonantor[100,101] have been demonstrated in recent years. Moreover, SiC has many impressive nonlinear optics properties, such as second-order nonlinearity, which contains second-harmonic generation (SHG)[9] and electro-optical effect,[102] third-order nonlinearity,[103] and even fourth-order nonlinearity.[104] SiC also has some unique advantages compared to the above-mentioned materials, such as long longevity color center defects[105] that can be used in quantum information processing. Additionally, SiC also has noteworthy acoustic properties[32] and has potential applications in future piezoelectric-optomechanics, microwave-optical signals, and other fields. We prospect that through techniques such as hybrid integration and heterogeneous integration, combined with other materials, it will help achieve efficient quantum frequency conversion and quantum information processing functions in the future.

In addition to these conventional materials mentioned above, we also notice the emergence of some novel material platforms that have shown great potential for active applications in integrated photonics, such as RE ion-doped materials, 2D materials, and QDs.

The wide transparent window and low loss characteristics of conventional optical materials are closely related to their wide and indirect bandgap features. However, these features also make it difficult to efficiently generate lasers or detect light in such materials. Therefore, some researchers have considered RE ion-doped materials, such as Erbium (Er)-doped,[10,11] Ytterbium (Yb)-doped,[106,107] Titanium (Ti)-doped,[108,109] and co-doped materials,[110,111] which are doped by RE ions whose energy level structure is relatively suitable for light emission and absorption. This is believed to be a significantly promising solution to achieve an on-chip light source and has shown massive impressive potential for applications of quantum nanophotonics.[112]

Compared to the III–V-based materials, RE ion-doped materials exhibit greater simplicity, adjustability, and expansibility in terms of the processes of device fabrication. For example, the co-integration of active and passive photonic devices by selective ion implantation[113,114] and stitched chips process[115] makes it more feasible for the future to achieve large scale photonic integration. Moreover, there are also some low-cost promising RE ion-doping technologies being developed, such as directly doping during the crystal growth process[116] and low-temperature diffusion doping.[117] Additionally, due to the relatively simpler structure of RE ion-doped material-based devices, it also shows the significant potential for hybrid integration applications in the near future.

2D materials, such as graphene,[118] black phosphorus (BP),[119] and transition metal dichalcogenides (TMDs),[120] are also types of novel material platforms with significant application potential in integrated photonics. In general, 2D materials consist of only one or a few layers of covalently bonded atom lattices.[121] Distinguishing from conventional materials, some 2D materials exhibit outstanding physical properties, such as high nonlinearity,[122] large absorption,[123] high optical anisotropy,[120] and high optoelectronics.[124] These unique properties greatly expand the degrees of freedom of the research studies in the field of integrated photonics, enabling the realization of the next generation photonic applications. Moreover, benefiting from the inherent physical properties of 2D materials, they can be directly integrated onto conventional optical materials through van der Waals (vdW) forces, which is called vdW integrations.[12,125,126] Compared to conventional material integration processes, such as wafer bonding, that require some extreme conditions, such as high temperature, vdW integration shows its unique potential for future hybrid and heterogeneous integration applications.

QDs are considered as artificial atoms.[13,14] Similar to the situation of RE ion-doped materials, introducing QD materials enables generating laser with specific wavelengths efficiently. Compared to the RE ion-doped material platform, QDs have a pure and versatile energy level structure, which can make the design and fabrication process easier and more flexible. Based on on-chip QD, researchers have demonstrated high-quality on-chip light sources,[127,128] deterministic single photon generation,[129–131] and other photonic applications.[132] QDs demonstrate remarkable potential for the next generation of integrated photonics, particularly in the field of integrated quantum photonics.[133–135] However, there are still challenges in terms of complex fabrication processes, uncertain positioning of QDs, lack of efficiency of coupling, etc. More innovations for the fabrication process of QDs, such as self-assembling methods,[136] need to be pioneered for further development of the QD material platform.

B. Technologies of hybrid material integration

Before introducing the hybrid integration technology, we will provide additional clarification on the definitions of hybrid integration and heterogeneous integration given in Sec. I to ensure consistency in the concept of hybrid integration mentioned throughout this Perspective. We also consult our definitions from Refs. 7, 28, 29, 137, and 138 to make sure that the arguments in this Perspective do not lose generality.

According to the common definitions, hybrid integration refers to the integration of fully processed dies, where the integration process is usually implemented during the packaging process, while heterogeneous integration refers to the integration of different materials, before the micro-/nano-structure fabrication processes. It should be noted that such a definition is not essentially sufficient, as there is no necessary connection between the order of integration and the degree of multi-material integration. For example, in the cases of LN–ChG hybrid waveguides[83] and LN–polymer hybrid waveguides,[139] although the material integration of LN with chalcogenide or polymer was implemented before the etching process, both the deposition of chalcogenide and the spin coating of polymer are very mature single-material-based processes, and the etching processes are also single-material-based. Therefore, they are both called hybrid integration. Distinctly, heterogeneous integration involves more complex multi-material processing and can often provide richer structures, such as achieving 3D integration.[93,140] To better illustrate the difference between the two kinds of integration technologies, we have drawn a simple diagram, as shown in Fig. 2.

Under certain circumstances, the choice between hybrid integration and heterogeneous integration depends on the specific characteristics of the materials, such as the coefficient of thermal expansion and chemical properties. For instance, it is quite challenging to employ the "strong" integration method of heterogeneous integration for two materials with a significant difference in their coefficients of thermal expansion. Moreover, the challenges of these two integration technologies are different. For hybrid integration, the fabrication of the photonic structure is not the main difficulty since it generally relies on a mature process based on a single material platform. The main challenge of hybrid material integration lies in solving the problems of material interfacing, which means achieving low-loss coupling of light from one material to another. This requires more explorations and developments of effective light coupling technologies, such as interface pre-processing,[141,142] alignment,[143–145] mode conversion structure design,[146,147] and so on. For heterogeneous integration, it generally needs to sandwich multiple materials together, forming a composite wafer or die, which requires a unified design, simulation, and fabrication approach. This entails ensuring compatibility between the various materials in the entire workflow. It is worth noting that these two technologies are not in competition with each other, but rather complement each other. Hybrid integration technologies can be used in scenarios where flexibility and cost-sensitivity are required, such as laboratory research and early-stage product functionality verification. Differently, the heterogeneous integration is more suitable for large-scale, high performance scenarios, such as commercial production. Moreover, the chip-scale photonic devices fabricated through heterogeneous integration can also be further integrated with other devices through hybrid material integration methods. The hybrid material integration technology and heterogeneous integration technology will continue to mutually promote and cooperate with each other in future development.

We classify the main integration processes into two categories: alignment-free processes, such as die and wafer bonding,[148–150] stitched chip,[115] and vdW integration,[125] and alignment-requiring processes, such as flip-chip integration[151] and transfer printing,[152] depending on whether it requires the precise alignment of devices. These two categories of integration processes can be used for either hybrid integration or heterogeneous integration, and we introduce them based on the compilation of some inspiring and impressive review articles during the past few years.[7,28,137,138,148]

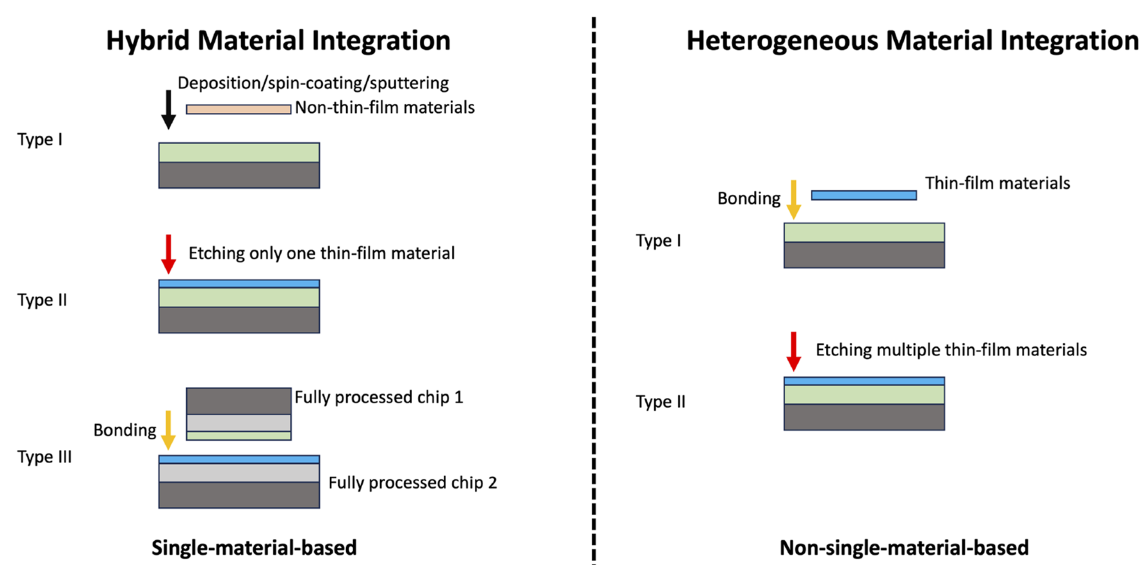

FIG. 2. Schematic of hybrid material integration and heterogeneous integration.

Alignment-free processes refer to the manufacturing processes that do not require precise alignment of structures of different materials (usually at the sub-micrometer level). For example, die and wafer bonding is commonly used in semiconductor processes, which refers to the bonding of wafers or dies (die-to-wafer or wafer-to-wafer) through covalent bond[149] or adhesives.[153] The former is usually called direct bonding, while the latter is called adhesive bonding. The advantage of direct bonding is that it can form a tighter connection with higher stability, while the advantage of indirect bonding is that it usually does not require high temperatures and can avoid the issues such as stress[149] caused by inconsistent thermal expansion coefficients or outgassing[154] caused by the formation of hydrophilic bonds. The schematic process flow of direct bonding is shown in Fig. 3(a). This process has been widely used in integrated photonics, especially in the integration of III–V materials and silicon materials.[155,156] In addition, we have noticed some novel integrated photonic processes based on die and wafer bonding, such as the photonic Damascene process,[63–66] which can achieve high-quality SiN devices[64] and heterogeneous integration of SiN with LN[16] and other materials. Furthermore, it has come to our attention that the stitched chip process was developed by Cheng's group[115] as shown in Fig. 3(b). This process involves placing a passive and an active chip on the same substrate and then splicing and curing the two chips to each other. Thereafter, use a femtosecond laser to weld the chips onto the substrate. Finally, the integration of active materials and passive devices is achieved followed by the photonic device fabrication. This pre-processing method is a very inspiring processing method that avoids the alignment issues of device structures. In addition, there is a relatively novel integration process called vdW integration.[125] VdW integration refers to directly stacking 2D materials on integrated photonic devices through van der Waals forces. This stacking can be achieved through methods such as mechanical exfoliation[157] and chemical vapor deposition (CVD).[158] VdW integration can usually bring unique optical and electrical properties to integrated photonic devices benefited from the novel properties of 2D materials. However, unlike the aforementioned technologies that more or less benefit from modern semiconductor processes, vdW integration is not mature enough. In addition, the relatively poor stability of the vdW integration still remains an issue to be addressed so that it requires more research to improve the preparation efficiency and quality at present. In summary, alignment-free processes typically require less precise control and complexity of process workflows. However, since alignment-free processes are usually completed in the pre-processing step before device fabrication, they impose some limitations on subsequent processing technologies, such as the compatibility of multiple materials.

Unlike alignment-free processes, alignment-requiring processes typically require the design of special structures, such as

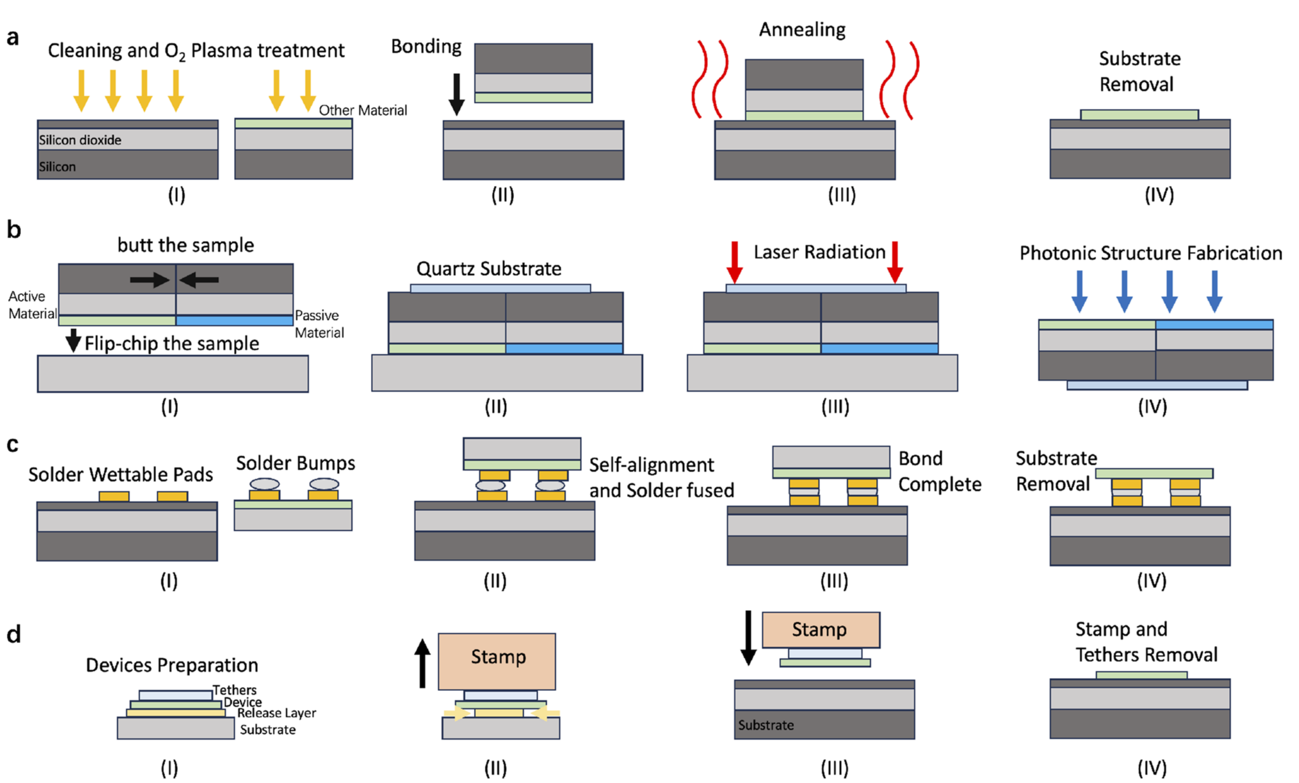

FIG. 3. Schematic process flow of hybrid material integration. (a) Die-to-wafer bonding processes (direct bonding, mainly referenced from Ref. 148). (b) Stitched chip processes (mainly referenced from Ref. 115). (c) Flip-chip integration processes (mainly referenced from Ref. 151). (d) Transfer printing processes (mainly referenced from Ref. 159).

flip-chip process,[151,160] or the use of precise transfer mechanisms to align devices, such as the transfer printing process.[161] These technologies are both early-developed integration processes in the field of integrated electronics and commonly used in hybrid integration currently[152,162] because it is typically performed after wafer or die fabrication, which has less stringent requirements for micro-/nano-fabrication processes. The key point of flip-chip integration is to fabricate conductive structures: the solder bumps and the under bump metallurgies on the substrate and chip as shown in Fig. 3(c); then, flip the chip and place it on the substrate, achieving self-alignment through the process shown in Fig. 3(c). Flip-chip integration has advantages such as maturity of processes, good thermal management, small contact area, high integration density, low cost, easy testing, and high yield.[28] It has been demonstrated for use in hybrid material integration, such as lasers[163,164] and high-throughput photonic interfacing.[165] Transfer printing is implemented by transferring micro-scale devices, which are called inks, from the native substrate to another substrate using an elastic stamp as shown in Fig. 3(d). Transfer printing has matured significantly over the years.[28] It is widely used in various hybrid integration applications, such as III–V-on-silicon distributed feedback laser,[166,167] III–V-on-SiN amplifiers and lasers,[168] high-speed modulator,[169] and photodetectors.[170] Transfer printing has various advantages, such as low cost, high speed, and high yields.[171] However, the transfer printing process, as well as the flip-chip process, is more suitable for transferring very small integrated photonic devices onto a large substrate compared to the alignment-free processes.[28] Under the demand for future hybrid material integration development, the aforementioned processes need to be more comprehensively utilized and developed.

C. Technologies of hybrid coupling

Besides the aforementioned integration processes, dealing with the problem of hybrid coupling is also very significant in hybrid material integration. Many factors can lead to unwanted losses when light passes through the interface. We have divided the problem of hybrid coupling into two aspects: light interfacing and light bridging. Many technologies have been developed to solve the hybrid coupling problems of these two aspects, such as grating coupling,[141,172,173] metasurface coupling,[142] and adiabatic tapers[147] for light interfacing and butt coupling,[143] mirror coupling,[174] and photonic wire bonding[175] for light bridging. We have compiled and summarized relevant works and some impressive review articles[176–179] to introduce these hybrid coupling methods.

Light interfacing focuses on how to achieve efficient coupling across material interfaces. Due to unwanted reflection and refraction that occurs when light passes through different materials at interfaces or due to mode mismatch caused by inconsistent mode distribution in two different material structures, it usually needs special photonic structure designs to avoid the aforementioned problems. For example, grating coupling is a technique that uses periodic structures, as is shown in Fig. 4(a), to provide a vector compensation in momentum space, which can achieve directional control of light propagation. This coupling technique can be used for both fiber-to-chip interfaces[141,180–182] and on-chip hybrid integration interfaces, which promotes the implementation of photonic applications, such as hybrid SiN platform,[183] hybrid photodetectors,[184] hybrid vertical-cavity surface-emitting laser (VCSEL),[185] and hybrid QD single-photon sources.[129] The benefits of grating coupling are that its structure is relatively simple, which makes it easy to design and implement. However, due to the reciprocity of the optical path and diffraction, at least half of the light will not be able to enter the waveguide inevitably, resulting in significant coupling losses (>3 dB). In response to this issue, some methods attempting to break this reciprocity have been proposed, such as slanted grating couplers[186] and chirped grating couplers.[187] These can reduce the loss associated with grating coupling to the order of a few decibels. In addition to this, researchers have developed another method, which is subwavelength grating (SWG)[142,188–193] coupling or metasurface coupling, to break the limitations from the subwavelength scale. Unlike grating coupling, the structure scale of metasurface coupling is much smaller than the wavelength as shown in Fig. 4(b), giving it higher degrees of freedom and the potential to overcome limitations of grating coupling and achieve lower coupling losses of sub-decibel level[194,195] and larger coupler spectral bandwidth.[196,197]

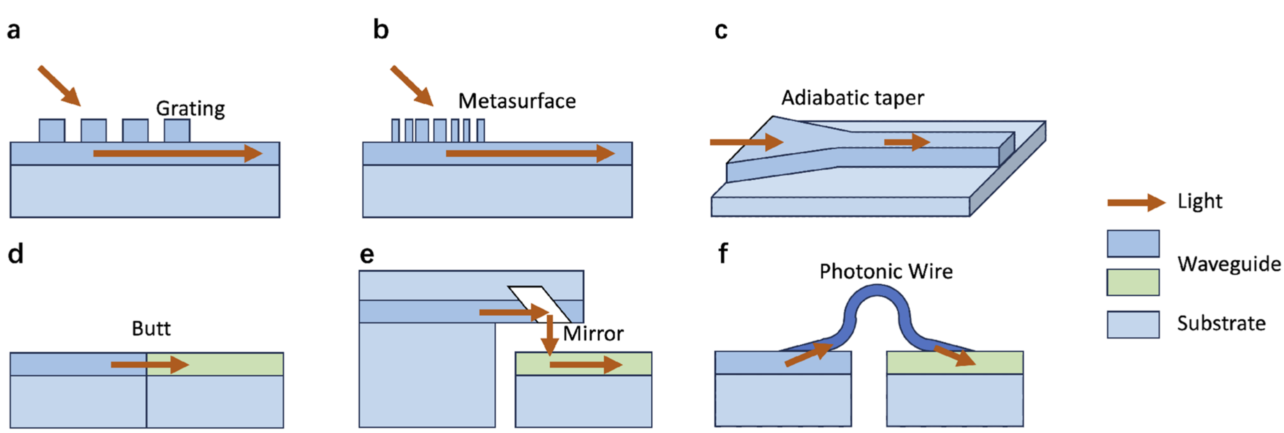

FIG. 4. Schematic of technologies of hybrid coupling. (a) Grating coupling. (b) Metasurface coupling. (c) Adiabatic taper. (d) Butt coupling. (e) Mirror coupling. (f) Photonic wire bond.

Nevertheless, metasurface coupling requires more complex design techniques and higher precision of fabrication. In the future, more optimization and machine-learning algorithms,[198–200] and even technologies such as large language models (LLMs),[201] will need to be applied to the design and manufacturing of complex structures with high degrees of freedom, such as SWG couplers, in order to break through the limitations of traditional methods. Moreover, adiabatic taper[147,202–206] is a gradual width change optical waveguide structure shown in Fig. 4(c) that can convert the waveguide mode from one material to another. This approach can achieve very low coupling losses (typically a few decibels or sub-decibel level)[207,208] and is relatively insensitive to wavelength[209] compared to the previous methods. Therefore, it is widely used in applications of hybrid integration or heterogeneous integration, such as lasers,[210] modulators,[211] and photodetectors.[212] Certainly, this approach has certain issues, one of which is the need for a relatively large footprint,[28] due to the requirement to ensure that the propagation distance of the light field is long enough to satisfy the adiabatic condition.

Light bridging refers to how to guide the light from one material to another. The most intuitive solution is to directly butt one material interface to another as shown in Fig. 4(d), which is namely butt coupling. Butt coupling[52,144,213–216] is a very commonly used method that is used to connect optical fibers to integrated photonic chips, as well as to connect two different integrated photonic chips. There are two key points, which are also challenges of fabrication, to achieve efficient butt coupling: waveguide alignment and end-face polishing. Either the waveguide mismatch or the end-face roughness will cause an increase in coupling loss. In addition to butt coupling, mirror coupling,[145,174,217–219] which is also called total-internal-reflection coupling, is a more complex strategy, which uses the waveguide-scale structure "mirror" to guide the light into an intricate pathway as shown in Fig. 4(e). This method unlocks the on-chip controllability of light in the vertical dimension, paving the way for the development of advanced 3D integrated photonic chips with increased complexity.[220] However, the crucial difficulty is the efficient fabrication of waveguide-scale "mirror." Since the mirror exhibits low robustness in many physical parameters, such as the angle of mirror, more techniques of the mirror fabrication need to be explored. Additionally, photonic wire bonding (PWB)[146,175,221] is another intuitive method. This method guides light to pass through two different materials by using a wire-like structure called photonic wire as shown in Fig. 4(f), which is very similar to wire bonding in the field of integrated electronics. The coupling loss of this method is as low as sub-decibel,[221] and it shows promising potential for future hybrid material integration applications.

In a practical scenario of the integration of multiple materials, it needs to consider both aspects of coupling mentioned above. For example, the adiabatic taper structure is used to achieve a high interface coupling efficiency in the scenario of the PWB technology developed by Koos' group,[175] and the simultaneous use of grating structure and mirror reflection structure has achieved excellent performance in 3D hybrid integrated silicon-based lasers.[146] It is noteworthy that even different methods of the same aspect can be combined to achieve better coupling performance, such as adiabatic SWG edge couplers.[222] It is believed that in the future, many early-developed coupling strategies will be more commonly seen in the design of hybrid integration.

D. The goal of hybrid material integration

In Sec. II A, we introduced the common materials used in hybrid integration, the technologies for achieving hybrid material integration, and the technologies of hybrid coupling. Overall, the development of hybrid material integration technology has greatly expanded the possibilities and diversity of integrated photonics, especially in the field of active photonic applications. Hybrid material integration enables a complete process from one to infinity in the field of integrated photonics, which means that we are no longer limited to a harder, from-zero-to-one process of finding a material that can meet all the requirements of not only passive devices, such as low transmission loss and wide transparency window, but also active devices, such as light control capabilities, coherent light emission, and absorption; instead, we can establish a comprehensive, cost-effective and fully functional integrated photonic platform through the hybrid integration technology, which is also the goal of hybrid material integration. Although there are still technical challenges in hybrid material integration, such as achieving low-cost, low-loss integration, and overcoming compatibility issues with specific materials, no fundamental physical limitations are preventing the resolution of these problems. It is believed with the increasing focus from researchers, these technical problems will be gradually resolved.

III. ACTIVE PHOTONIC APPLICATION

The ultimate goal of integrated photonics, whether for classical applications or quantum applications, is to implement functions of light generation, amplification, processing, detection, and even storage, by integrating various devices on a chip. However, relying solely on passive photonic devices, such as waveguides and microcavities, is far from sufficient to meet all these requirements. Active devices, which have "controlling" capabilities, need to be introduced to achieve the ultimate goal. Since active device needs to rely on specific conversion processes, such as electro-optic effect for electro-optic conversion, nonlinear optics effects for optical–optical conversion, piezoelectric effect for electro-acoustic conversion, and opto-mechanical effect for photo-acoustic conversion, it is nearly impossible to fulfill all the above abilities in a single material platform. The hybrid material integration technology provides a practical alternative. Moreover, it is worth mentioning that hybrid material integration usually exhibits a unique "$1 + 1 > 2$" effect since hybrid-integrated materials can greatly reduce the losses and mechanical vibrations caused by chip-to-chip connections. We will demonstrate the above points of view through some remarkable work of hybrid material integration for the active photonic applications we have noticed in recent years.

A. Hybrid laser

In recent years, research on integrated photonics based on the hybrid material integration technology has shown a booming trend, especially in the field of high-performance on-chip laser sources. The development of an efficient on-chip integrated laser in silicon-based photonics has long been considered a holy grail,[137] particularly in the context of growing demands for data processing and transmission. Over the years, numerous techniques have been employed, including

QD lasers[223] and on-chip Raman lasers,[224] to address the limitations of the silicon platform, which is characterized by indirect bandgaps. However, these methods have not been able to break through the limitations of a silicon platform, making it still difficult to achieve a compact, energy-efficient, and robust laser source.[138] Fortunately, we are glad to find numerous remarkable works showing the great potential of the hybrid integration technology in achieving efficient on-chip laser generation in recent years. Here, we will introduce these impressive works.

High-performance on-chip lasers can be achieved through the hybrid integration technology in two main ways. The first method is to integrate packaged structures of both reflected semiconductor optical amplifier (RSOA) or laser diode and on-chip gainless photonic devices. This approach allows for narrowing the linewidth, output modulation, and frequency locking through on-chip structures. As early as 2012, Morito's group demonstrated the hybrid integration of packaged RSOA with an on-chip microring resonator and modulator structure, achieving a laser output power of 15.0 mW and a minimum interface coupling loss of 1.55 dB,[225] as shown in Fig. 5(a). In 2014, Boller's group demonstrated the hybrid integration of RSOA with Si_3N_4/SiO_2 platform, resulting in a laser output power of 5.7 mW with a linewidth of 24 kHz.[226] In 2016, researchers from the Oracle Networking Group successfully fabricated high-density laser sources by combining RSOA with a SOI chip using a non-intrusive back-end-of-line (BEOL) integration method. They achieved an output power of 10 mW and a coupling loss of 5% by reducing the thickness of the metal/dielectric layers.[227] In 2018, Koos' group achieved the integration of InP laser arrays and silicon-based modulators using the PWB coupling method, with a coupling loss of only 0.4 dB[221] as shown in Fig. 5(b). They also integrated InP RSOA with silicon-based structures using the same method, resulting in a side-mode suppression ratio (SMSR) of 40 dB and a linewidth of 105 kHz.[228] In 2023, Lipson's group demonstrated the hybrid integration of a packaged multi-mode FP laser diode with on-chip microring, enabling widely tunable and narrow-linewidth chip-scale laser from near-ultraviolet to near-infrared wavelengths[229] as shown in Fig. 5(c). In addition, in the same year, Lin's group demonstrated a self-injection locking laser by using hybrid integration, achieving linewidth narrowing of an external cavity laser through on-chip PPLN microring and obtaining a laser output with a linewidth of 4.7 kHz.[230] In addition, in the same year, Marandi's group demonstrated a hybrid integration ultrafast mode-locked laser by combining a III–V gain medium and a LN phase modulator.[15] We believe that these hybrid integrated laser configurations have great development prospects because they can greatly exploit on-chip devices to overcome the drawbacks of traditional semiconductor lasers, such as wide linewidth and limited tunability, and achieve high-quality chip-scale lasers.

In addition to the above method, we have also noticed another promising hybrid integrated laser, which is the integration of an externally packaged semiconductor laser as a pump source and a microcavity based on RE ion-doped material as a laser cavity and gain media. The advantage of this method is that compared to the previous method, it can achieve narrower linewidth and

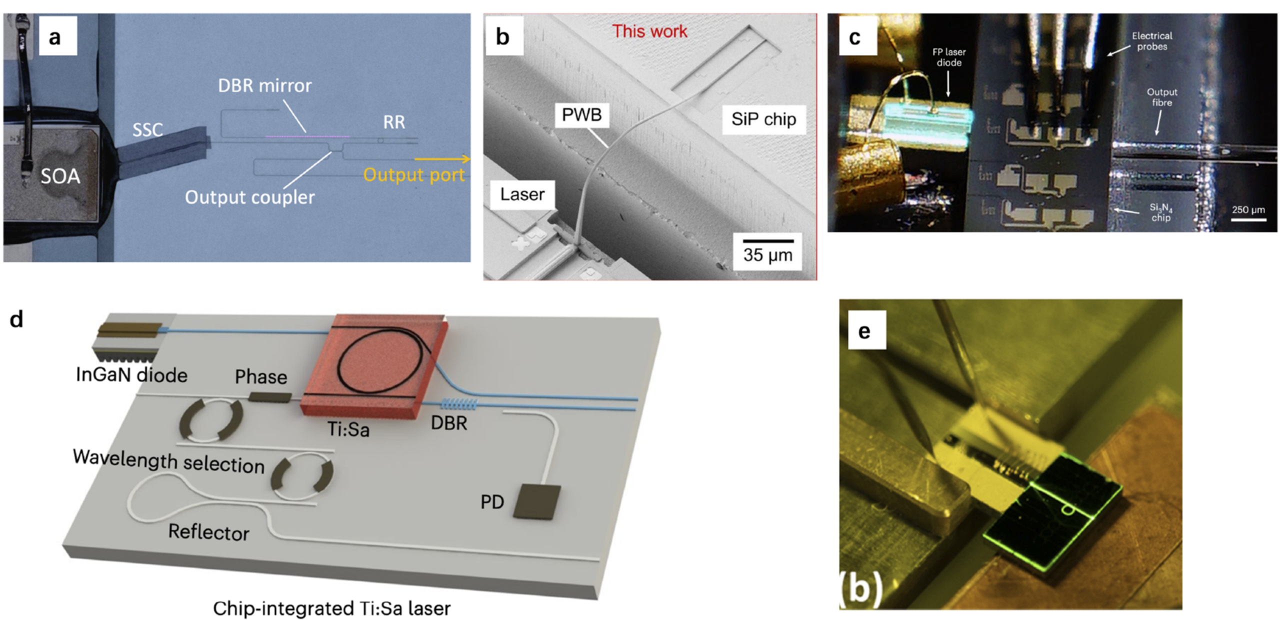

FIG. 5. Hybrid laser. (a) Hybrid integration of packaged RSOA with photonic circuits. (b) Hybrid integration of silicon photonic circuits and InP lasers by photonic wire bonding. (c) Widely tunable and narrow-linewidth hybrid lasers. (d) Photonic-circuit-integrated titanium/sapphire laser. (e) Laser diode-pumped compact hybrid lithium niobate microring laser. (a), (b), and (e) Reprinted with permission from Billah *et al.*, Optica **5**(7), 876–883 (2018). Copyright 2018 The Optical Society; Tanaka *et al.*, Opt. Express **20**(27), 28057–28069 (2012). Copyright 2012 The Optical Society; and Zhou *et al.*, Opt. Lett. **47**(21), 5599–5601 (2022). Copyright 2022 The Optical Society. (c) and (d) Reproduced with permission from Corato-Zanarella *et al.*, Nat. Photonics **17**(2), 157–164 (2023). Copyright 2023 Springer Nature and Wang *et al.*, Nat. Photonics **17**(4), 338–345 (2023). Copyright 2023 Springer Nature.

higher tunability of laser output and has lower coherence requirements for pump laser, which gives it certain advantages in the future large-scale integrated photonic applications. In 2022, Tang's group achieved laser generation from 730 to 830 nm by hybrid integrating an InGaN diode pump source with a microring resonator on Ti:sapphire, and the laser threshold was reduced by one to two orders of magnitude compared to bulk Ti:sapphire, reaching 6.5 mW[109] as shown in Fig. 5(d). In the same year, Cheng's group also demonstrated the integration of laser diodes with microring resonators on Er:TFLN, achieving single-mode laser generation with a threshold power of only 6 mW[231] as shown in Fig. 5(e). In 2023, Kippenberg's group achieved an on-chip tunable laser by fully integrating a laser diode, undoped tunable SiN devices, and RE ion-doped SiN waveguides, demonstrating extremely low linewidth laser output at 50 Hz, as well as high SMSR and high-speed tunability.[16,114] We believe that this hybrid integrated laser configuration based on RE ion-doped thin-film materials has great potential in the future, as they can not only help achieve more beneficial laser performance but also make it easier to combine mature on-chip thermo-optic, electro-optic, and even acousto-optic manipulation technologies to realize more versatile on-chip laser sources.

B. Hybrid optical frequency comb

Optical frequency comb (OFC) is regarded as a revolutionary discovery that benefited from its specific equidistant spectral lines, which immensely promotes the development of optical communication,[232] precision metrology,[233] molecule detection,[234,235] and many other areas. However, the technology of comb generation is highly limited within the laboratory due to the demand of high power consumption and complexity of the device. In recent years, the rapid development of integrated photonics has promoted the implementation of integration of a mirocomb generator.[236] Nevertheless, it is still hard to achieve a fully chip-scale high-performance OFC source due to its high requirements for stability, maneuverability, and the high quality of the pump source. Fortunately, hybrid integration is considered a superior method for solving the above issues attributed to its full combination of advantages of various material platforms. We have noticed that in recent years, there have been numerous excellent works achieved on-chip OFC source through hybrid integration, including mode-locked OFC, Kerr OFC, and gain-switched OFC. We will introduce these works separately in the below context.

Hybrid integrated mode locking OFC is realized by integrating the on-chip laser to the carefully designed waveguide. In 2019, Boller's group[237] successfully achieved the output of mode-locked OFC by butt-coupling a monolithic RSOA to the SiN photonic circuit, corresponding to a linewidth of only 34 kHz, which is far lower than any reported comb laser. Subsequently, in 2021 and 2023, they successively implemented the generation of 25 nm broadband OFC[238] and sub-GHz repetition rate OFC with an ~40 MHz wide locking range.[17] These results demonstrate that the implementation of hybrid integration could perfectly solve the problems in traditional methods. However, it seems that the mode-locking method is not the best scheme due to the limited tunability, weak coherence, and narrow bandwidth.

Compared to the above method, hybrid integrated Kerr OFC seems more promising to achieve high-performance comb source due to its high stability, coherence, and broad bandwidth, which arise from the Kerr effect of the material. In 2018, Lipson's group successfully observed that the soliton comb formation corresponds to a frequency span exceeding 8 THz with the input current below 100 mW, by coupling a III–V RSOA gain chip to a high-Q microresonator on the SiN platform[239] as shown in Fig. 6(a). It demonstrates the potential to realize a portable and efficient OFC source powered solely by batteries. After a year, Kippenberg's group demonstrated the simultaneous formation of dissipative Kerr solitons[240] as shown in Fig. 6(b). In this work, an InP multi-frequency laser diode chip is directly butt-coupled to a SiN photonic chip with a microresonator, which operates at an electronically detectable sub-100-GHz mode spacing with less than 1 W of electrical power. In 2021, Papp's group proposed a similar structure as Kippenberg's, which presents an octave-spanning OFC in support of future precision timing applications.[241] Moreover, in 2020, Bowers' group achieved integrated turnkey soliton microcombs by introducing the DFB laser. In this system, solitons are immediately generated by turning the pump laser on, thereby eliminating the need for photonic and electronic control circuitry[242] as shown in Fig. 6(c). Thanks to the remarkable achievements of chip-scale Kerr OFC, it is believed that the hybrid integrated Kerr OFC will be the preferred choice in the future for the lower power, lower cost, lower complexity, and higher efficiency OFC source.

Additionally, hybrid integrated gain-switched OFC, which is realized through the gain-switched pump laser, should also be noted. In 2022, Chen's group successfully achieved an on-chip comb source by using a hybrid integrated self-injection locking DFB laser[243] as shown in Fig. 6(d). On-chip gain-switched comb is another alternative way to achieve free-spectral-range (FSR)-adjustable OFC source.

In general, hybrid integration is of great significance for the miniaturization and commercialization of OFC sources. More importantly, we can utilize diverse properties of various materials and structures. Nevertheless, the potential of hybrid integration is not fully realized at present. For instance, we have noticed that Kippenberg's group have proposed a solution for Kerr OFC generation by a photonic crystal cavity recently,[244] which indicates that the birth of a highly dispersion-tunable and fully integrated on-chip Kerr OFC source in the future is expected, by leveraging the advantages of hybrid integration. We believe that hybrid integration will bring more possibilities to the development of the OFC in the future.

C. Hybrid modulator

Modulators are considered to be the most crucial component in the field of optical communications. Achieving a high bandwidth, high modulation efficiency, and low loss modulator is a primary goal for researchers. Previously, the method of implementing modulators on silicon was through the plasma dispersion effect by carrier.[245] However, this method resulted in relatively high losses, and there were still bottlenecks in modulation efficiency and bandwidth, making it difficult to meet the growing demands of optical communications. In recent years, researchers have discovered that TFLN has profound potential for high-performance modulators. Lončar's group has demonstrated a high-bandwidth modulator based on TFLN with CMOS-compatible voltage.[77] However, TFLN is not compatible with current CMOS processes, and the processing of TFLN is still difficult and expensive. Instead, we have noticed

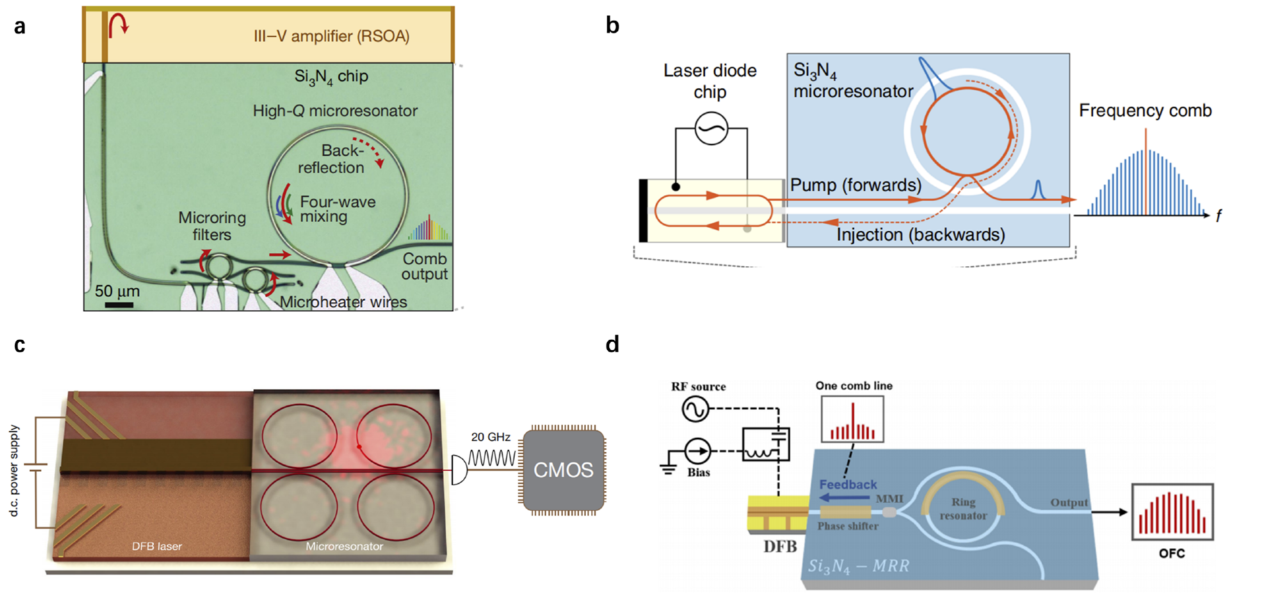

FIG. 6. Hybrid optical frequency comb. (a) Hybrid integration of packaged RSOA with frequency comb generator. (b) Electrically pumped photonic integrated soliton microcomb. (c) Integrated turnkey soliton microcombs. (d) Hybrid integrated gain-switched optical frequency comb source. (a) and (c) Reproduced with permission from Stern *et al.*, Nature **562**(7727), 401–405 (2018). Copyright 2018 Springer Nature and Shen *et al.*, Nature **582**(7812), 365–369 (2020). Copyright 2020 Springer Nature. (b) Reproduced from Raja *et al.*, Nat. Commun. **10**(1), 680 (2019). Author(s), licensed under a Creative Commons Attribution 4.0 License. (d) Reproduced from Shao *et al.*, IEEE Photonics J. **14**(1), 6613606 (2022). Author(s), licensed under a Creative Commons Attribution 4.0 License DEED.

that in recent work, many researchers have used the hybrid material integration technology, which provides a novel approach that combines the properties of LN material and the processing advantages of CMOS-compatible materials. This approach avoids the etching of LN, which means that all the etching processes are done on CMOS-compatible material platforms. This approach is very commonly seen in the field of modulators.

In 2014, Reano's group demonstrated the integration of TFLN on a pre-etched SOI microring resonator through wafer bonding, achieving an electro-optic bandwidth of 5 GHz and demonstrating digital modulation up to 9 Gbps[246] as shown in Fig. 7(a). In 2018, Mookherjea's group integrated non-etched LN with an etched Mach–Zehnder modulator (MZM) on SOI, achieving an electro-optic bandwidth beyond 106 GHz[247,248] as shown in Fig. 7(b). During 2019, Cai's group achieved hybrid integration of LN and SOI devices to realize a Michelson interferometer modulator, achieving a modulation bandwidth of 17.5 GHz and a modulation efficiency of 1.2 V cm.[249] In the same year, they also demonstrated a MZM with LN and SOI hybrid integration, showing a modulation efficiency of 2.2 V cm, at least 70 GHz of electro-optic bandwidth, and a digital modulation of 112 Gbps[18,211] as shown in Fig. 7(c). In 2022, Mookherjea's group used coplanar traveling wave electrodes to demonstrate an electro-optic bandwidth exceeding 110 GHz, capable of handling 110 mW laser power with an insertion loss of only 1.8 dB and a modulation efficiency of 3.1 V cm for LN and SOI hybrid integrated MZM.[250] In 2023, Su's group demonstrated a hybrid lithium tantalite–silicon ring modulator with the bidirectional wavelength tuning efficiency of 12.8 pm/V and 3-dB bandwidth >20 GHz.[87] It is believed that the hybrid integration of LN or LT with other lower-loss materials, such as SiN, will offer the possibilities for achieving a more high-performance chip-scale modulator.

We have noticed that the hybrid integration technology has shown great potential not only in electro-optic modulators but also in acousto-optic modulators.[251] In 2020, Bhave's group hybrid integrated an AlN piezoelectric actuator with a SiN microring resonator, achieving high-speed control of the optical microcavity through high-overtone bulk acoustic wave resonances (HBARs)[98] as shown in Fig. 7(d). In the same year, Sun's group demonstrated a bound state in the continuum (BIC) mode acousto-optic modulation by hybrid integrating polymer waveguides on a non-etching LN substrate.[139] During 2022, Li's group achieved hybrid integration of a LNOI substrate with chalcogenide glasses (ChGs), realizing an integrated acousto-optic modulator with a non-suspended structure by utilizing LN's superb acoustic performance[83] as shown in Fig. 7(e). This inspires us that through the technologies of hybrid material integration, we can avoid some sophisticated on-chip acoustic structures, reduce processing difficulties, and better utilize the advantages of various materials.

IV. CHALLENGES AND PERSPECTIVES

Many fabrication technologies of diverse materials and integration techniques to achieve a hybrid integration have already grown mature, which means that the from-zero-to-one process is close to completion over the past few years. At the same time, the great advantage of the hybrid integration technology that can break through the limitations of traditional monolithic material platforms

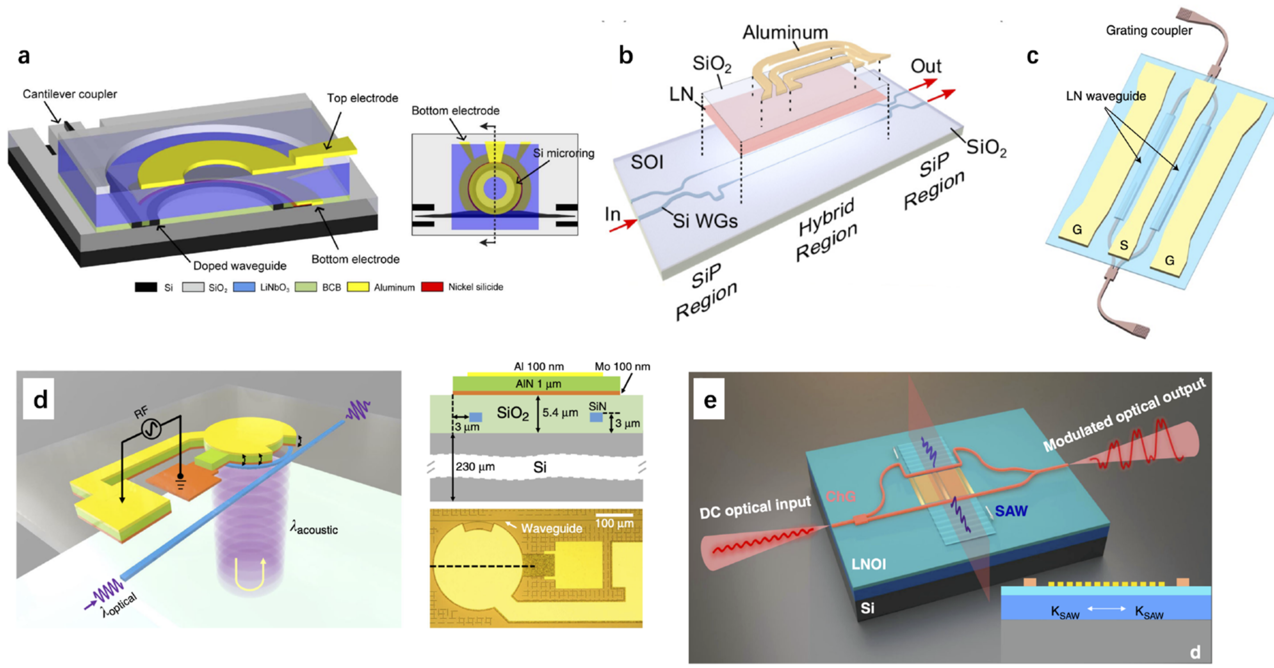

FIG. 7. Hybrid modulator. (a) Hybrid silicon and lithium niobate electro-optical ring modulator. (b) Bonded thin film lithium niobate modulator on a silicon photonic platform. (c) Hybrid silicon and lithium niobate Mach–Zehnder modulators. (d) Hybrid integrated photonics using bulk acoustic resonators. (e) Acousto-optic modulation using non-suspended thin-film lithium niobate–chalcogenide hybrid waveguides. (a) and (b) Reprinted with permission from Chen *et al.*, Optica **1**(2), 112–118 (2014). Copyright 2014 The Optical Society and Weigel *et al.*, Opt. Express **26**(18), 23728–23739 (2018). Copyright 2018 The Optical Society (c) Reproduced with permission from He *et al.*, Nat. Photonics **13**(5), 359–364 (2019). Copyright 2019 Springer Nature. (d), (e) Reproduced from Wan *et al.*, Light: Sci. Appl. **11**(1), 145 (2022). Author(s), licensed under a Creative Commons Attribution 4.0 License and Tian *et al.*, Nat. Commun. **11**(1), 3073 (2020). Author(s), licensed under a Creative Commons Attribution 4.0 License.

is not solely demonstrated in realizing laser sources, OFC sources, and modulators but also in achieving photodetectors,[20–24] integrated quantum photonic circuits,[46,252–255] and many other fields. Moreover, the concept of hybrid integration is not limited to active photonics. It can also be considered to be the hybrid integration of multiple physics systems with a photonic system, such as phononic systems,[256] superconducting qubit systems,[257] and electronic–photonic systems.[258] These hybrid integration technologies will lead us into a stage of one-to-infinity development.

However, despite the bright vision of hybrid integration, some tangible obstacles to achieving hybrid integration still exist. Major challenges are the relatively high cost of hybrid material integration, which is chiefly due to the fact that the requisite technology for hybrid integration typically involves substantial equipment expenditures, and ancillary processes leading to diminished production yields, making it difficult for most researchers to adopt hybrid integration technologies. Further commercial exploration is necessary, specifically in the realm of commercializing highly customized hybrid integration process services. In addition, the challenge of hybrid integration also lies in its highly interdisciplinary nature. Achieving the integration of multiple materials and developing corresponding integrated photonic applications require not only a foundation in basic sciences, such as materials, chemistry, and physics, but also support from advanced engineering technologies, including the algorithm development for simulation, precision mechanical control, thermal management techniques, and micro-/nano-fabrication. Therefore, pursuing broader collaboration of the researchers is the trend for future development in the field of integrated photonics with multiple materials. Another challenge is a practical engineering task that a significant amount of similar, repetitive process exploration of design, simulation, fabrication, packaging, and testing are required. A well-established workflow for one material system often requires starting from scratch when dealing with a different type of material. Additionally, extensive exploration is needed for tasks such as ensuring thermal stability compatibility, electronic-photonic compatibility, and fabrication process compatibility between material systems. One promising solution to this problem is building a complete process design kit (PDK),[195,259] which is also needed for large-scale and high-yield fabrication of photonic integrated circuits, especially when multiple materials are involved. In the longer term, it is also necessary to achieve standardization at the packaging level and establish a photonic assembly design kit (ADK)[260] to lay the foundation for the widespread adoption of hybrid integration. In addition to solving specific challenges within the hybrid integration technology, it is also very worthwhile to explore how to leverage the advantages of hybrid integration to achieve specific goals in the field of integrated photonics, such as realizing practical integrated photonic quantum computing, optical computing, precision sensing, and high-capacity communication. After all, in the midst of difficulty lies opportunity.

Hybrid material integration that aims to fully leverage the advantages brought by multiple materials and structures is very promising to achieve the effect of "$1+1>2$," or in other words, "more is different"[261] for integrated photonics.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Chengyu Chen and Yuping Chen contributed equally to this work.

Chengyu Chen: Conceptualization (equal); Data curation (lead); Investigation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yuping Chen**: Conceptualization (lead); Data curation (supporting); Funding acquisition (lead); Investigation (supporting); Project administration (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal). **Zhifan Fang**: Data curation (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Rui Ge**: Writing – review & editing (supporting). **Jiangwei Wu**: Conceptualization (lead); Funding acquisition (lead); Investigation (supporting); Project administration (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (supporting). **Xianfeng Chen**: Supervision (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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