Foundry's Perspective on Laser and SOA Module Integration with Si-Photonics

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Abstract: An effective solution to integrating light source onto silicon photonics platform would be highly useful. Here, we discuss the integration solutions (i.e., hetero-epitaxial, heterogeneous and hybrid integration) and present foundry's perspective toward implementing of such.

1. Introduction

Silicon photonics has been increasingly gaining commercial traction. It has also been already explored in many applications, such as telecommunications, biosensing, remote sensing (LiDAR), and computing. It initially leverages the maturity of CMOS (complementary metal-oxide-semiconductor) processing techniques in the electronics industry and is today a growingly distinct field on its own right - spanning billion-dollar market share. As the industry grows, development routines are being simplified much to the practical convenience of users/customers. These include Process Design Kit (PDK) and packaging solutions. Open-access photonics foundries such as Advanced Micro Foundry (AMF) provides PDK devices library to enable silicon photonics designers to conveniently adopt PDK devices for their respective applications without the need to develop individual devices common to the platform. However, while silicon photonics PDK provides a library comprising a plethora of silicon photonics devices, the lack of direct bandgap in crystalline silicon leads to the typical exclusion of on-chip light source from the library. While this is evidently a key bottleneck that impedes full deployment of silicon photonics devices, from foundry stand-point, there are two main general approaches to address this: laser integration onto silicon platform via packaging [1], and the more ambitious silicon-based lasers [2]. The former is today regarded as the more practical approach and is adopted by many.

2. Integration Technology

There have been multiple integration process flows for laser and SOA module integration using silicon photonics. As shown in Table 1, these process flows can proceed in three major directions i.e., hetero-epitaxial integration, heterogeneous integration, and hybrid integration. These heterogenous and hybrid integration approaches have their own respective advantages and disadvantages. The choice of integration approach largely depends on the application requirement, such as integration scale, cost, the quantity of laser diode to be integrated onto the silicon platform.

Table 1. Major solutions for light source integration

Hetero-epitaxial integration	Germanium or Germanium-tin laser [3]
	Epitaxial III-V material on silicon laser [4]
	Rare-earth-doped Al_2O_3 laser by external optical pumping source [5]
Heterogeneous integration	Molecular bonding [6]
	Adhesive bonding [7]
	Micro-transfer-printing bonding [8]
Hybrid integration	Passively aligned and flip-chip bonding [9]
	Photonic wire bonding [10]

In hetero-epitaxial integration approach, suitable direct-gap material as optical gain material for laser emission is being grown on silicon-compatible platform. Of the various direct-gap materials, there is typically a tradeoff between material compatibility and lasing performance between germanium-based laser and III-V materials. While germanium-based laser (such as germanium-tin laser) offers greater integrability due to its fabrication line compatibility on silicon photonics platform it lags behind III-V materials in terms of lasing performance (e.g., III-V material-based lasers require lower operating power and have lower side mode suppression ratio SMSR). III-V material-based laser such as of epitaxial III-V materials on silicon has a larger lattice constant mismatch with silicon, as it thus more challenging to be grown directly on silicon-based platform. III-V material process also requires a larger thermal budget and substantially thicker buffer layer for compensation of lattice constant mismatch and defect reduction. There is currently no hetero-epitaxial integration solution that can address the tradeoff.

In heterogenous integration, optical gain material and silicon-based optical waveguides are physically bonded together via optical coupling based on adiabatic coupling or mode overlapping method. Three major approaches to this are molecular bonding, adhesive bonding and micro-transfer printing. Molecular bonding is a direct bonding process using van der Waals forces to attach two heterogeneous materials with strong bonding strength. Although wafer-level process for molecular bonding is available through wafer-to-wafer and die-to-wafer methods for medium- and large-scale manufacturing, its process tolerance is very small and is typically limited to silicon-based chips with smaller footprint that require fewer number of laser diodes due to the significantly higher cost of III-V materials. On the other hand, adhesive bonding, which uses adhesive material (polymer or metal) to bond different materials together, has larger fabrication tolerance on surface contamination and roughness, requires lower temperature for bonding process (thus involves lower possibility of introducing structural damage to III-V laser diodes), and offers higher scalability with silicon wafers compared to molecular bonding. However, good optical coupling is often an issue in adhesive bonding due to the following reasons: i. the thickness of adhesion polymer or metal is difficult to control, ii. adhesion polymers generally have lower thermal conductivity, and iii. it is common for metal adhesives to introduce optical loss and metal contamination. Micro-transfer-printing bonding is a distinct heterogenous integration approach that uses a sacrificial transfer stamp (e.g., polydimethylsiloxane, PDMS) to bond fabricated laser diode onto silicon chips. While the method enables manipulation of laser diodes with high-accuracy with massively parallel (and therefore high) throughput assembly of laser diodes onto silicon chips, its requisite 'release-and-stamp' process onto III-V material increases process complexity and integration cost with occasional repeatability and reliability concerns. In general, because these heterogenous integration approaches need additional back-end customized manufacturing process and tools for III-V materials such as additional III-V material etching, and cleaning capability, the approach is less compatible for current standard commercial silicon photonic foundry.

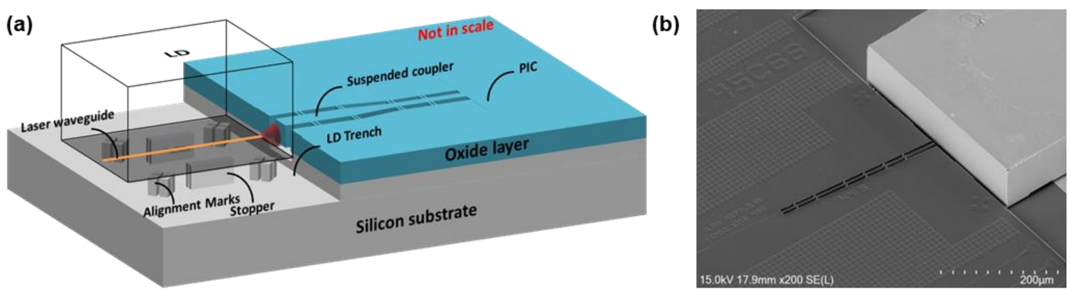

Fig. 1. (a) Schematic of the suspended coupler designed for coupling to laser diode on SOI platform. (b) SEM of the LD bonded silicon photonics chip.

In hybrid integration approach, fabricated III-V material-based laser diodes are integrated onto silicon chips by using either edge coupler or grating coupler to couple light into the chips. The approach enables good die comprising laser diode to be selectively picked for the integration process – thus ensuring a significantly higher device performance for both laser diode and silicon chips, compared to other integration solutions. In AMF, the hybrid integration approach is adopted. We developed a hybrid integrated platform on 200-mm silicon-on-insulator (SOI) wafer, as shown in Figure 1. To realize the integration, additional alignment marks are patterned for passive alignment of laser diode onto the silicon chip, and the stopper is defined to hold the laser diode and control the height of silicon chip to realize maximum optical mode overlapping. The shallow trenches ensure there is sufficient physical space to place laser diode onto the silicon chip. Using under-bump metallurgy (UBM) and solder bump, electrical trace and strong permanent bonding between laser diode and Si chips, respectively can be achieved. This enables integration of III-V material such as GaAs, lnP, GaN for laser diode and also other materials for isolator or high-speed modulator (such as lithium niobate, $LiNbO_3$).

3. Discussion

Among the various optical coupling methods via hybrid integration, low profile lateral scheme with laser diode (LD) butt coupling to silicon waveguide through spot-size converter is a promising optical coupling method. The approach offers the advantage of providing the freedom for individual optimization and fabrication of both laser diode and silicon photonics chips on different material platforms prior to the integration, and spatially freeing up the top surface of the silicon photonics chips for electrical and thermal connections to the active device. AMF has been actively developing this solution for years. For large-scale volume production of the laser/SOA module integration with silicon photonics to materialize, the items to be addressed and optimized are as follows:

1. *Laser/SOA module customization*
   To achieve a repeatable and reliable bonding performance, the laser/SOA module needs to include a set of alignment marks with high vertical alignment overlay accuracy between the marks and light source waveguide during the bonding process. This ensures high accuracy between the light emission center and the reference plane. Another possible option is to realize a laser/SOA module with reduced beam divergence to improve the coupling efficiency between the light source and silicon photonics chips.

2. *Coupling scheme*
   One of the major challenges in hybrid integration approach is the need for flip-chip bonding and passive alignment technology. These require low loss coupling scheme with wide alignment tolerance coupling to the divergent beam output from commercial laser/SOA module. There are two major directions to improve the packaging performance. One is to design low loss spot size converter (SSC), while the other is to have larger light source beam spot diameter (e.g., to reduce the beam divergence for laser diode) or directly using the SOA module instead. Suspended SSC, which could provide < 2dB coupling loss and micron size tolerance, is a viable option to achieve high coupling efficiency (mode matching) and reasonable alignment tolerance required for low loss coupling from LD to optical waveguide. However, the mechanical stability of the suspended structure needs to be considered during the product packaging. Developing a SiN based SSC on top of SOI is an alternative solution and the combination of silicon and SiN enhance the design freedom not only on SSC but also on a variety of other key function components. Currently, SiN-on-SOI has been developed as standard platform in several photonics foundries. In particular, AMF has been providing both LPCVD SiN and PECVD SiN integrated with 220-nm-SOI platforms with PDK support.

3. *Metallization*
   In terms of solder material and related bonding temperature, there are mainly two choices, which is AuSn (bonding temperature of ~300ºC) and SnAg (bonding temperature of ~220ºC) with different corresponding metallization processes. Liftoff processes are widely used to form the AuSn solder, while ECP (electroplating) processes are employed for SnAg solder formation. Compared with liftoff process, ECP is much more desirable for volume production. However, there is also one factor to be considered for the selection of solder material. Besides the light source bonding, the electronic chips, e.g., TIA, drivers, would also need to be attached on the silicon photonics chips. Having different bonding temperature could eliminate the potential cross effects between the light source chips and electronic chips bonding processes.

4. *Reliability Assurance*
   Reliability test should be considered on the hybrid light source integration silicon photonics chips/wafers for future production. GR-468-CORE (Telcordia Technologies Generic Requirements) and JEDEC (Joint Electron Device Engineering Council) JEP001 are the good reference as the starting point for the reliability assessment.

5. *Other packaging related discussions*
   Other issues to be considered to pave the way for scaled-up commercialization of hybrid light source integration solution include epoxy filling/curing, device passivation, heat dissipation, and thermal isolation between chips.

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