Extremely compact hybrid III-V/SOI lasers: design and fabrication approaches

Olesya Bondarenko*, Cheng-Yi Fang, Felipe Vallini, Joseph S. T. Smalley and Yeshaiahu Fainman

University of California San Diego, 9500 Gilman Drive, San Diego, CA 92093, USA
*obondarenko@eng.ucsd.edu

Abstract: In this manuscript we discuss state of the art hybrid integration techniques and III-V/Si active components with an emphasis on hybrid distributed feedback (DFB) lasers for telecom applications. We review our work on ultra-compact III-V/Si DFB lasers and further describe design considerations and challenges associated with electrically pumped hybrid lasers. We conclude with a perspective on DFB lasers with extremely small footprint, a direction for future research with potential applications to densely-packed optical interconnects.

© 2015 Optical Society of America

OCIS codes: (140.3490) Lasers, distributed-feedback; (050.2770) Gratings; (230.3120) Integrated optics devices; (130.5990) Semiconductors; (230.0250) Optoelectronics; (160.3918) Metamaterials.

References and links
42. C. Kittel,
48. M. Cantoro, C. Merckling, S. Jiang, W. Guo, N. Waldron, H. Bender, A. Moussa, B. Douhard, W. Vandervorst,
47. C.-W. Hsu, Y.-F. Chen, and Y.-K. Su, “Heteroepitaxy for GaAs on Nanopatterned Si (001),” IEEE Photon.
51. D. H. Ghafouri-Shiraz,
49. A. Lee, Q. Jiang, M. Tang, A. Seeds, and H. Liu, “Continuous-wave InAs/GaAs quantum-dot laser diodes
54. A. W. Fang, R. Jones, H. Park, O. Cohen, O. Raday, M. J. Paniccia, and J. E. Bowers, “Integrated AIGaInAs-
56. B. R. Koch, A. Alduino, L. Liao, R. Jones, M. Morse, B. Kim, W.-Z. Lo, J. Basak, H.-F. Liu, H. Rong, M.


1. Introduction

Global data traffic is expected to exceed the zetabyte mark by 2017 due to the exponentially growing number of Internet applications for stationary and mobile devices, as well as the number of their users, according to the recent Cisco Visual Network Index (VNI) forecast. Several new trends are driving this rapid expansion, including high definition mobile-to-mobile video streaming, Internet of Things phenomena and rapid cloud computing [1]. Support of high information density requires powerful processing capabilities for fast data access. This is important not only in datacenters but also in computational research labs and supercomputers, where large amounts of data have to be processed quickly. Consequently, efficient information transfer between microprocessor cores, memory and peripherals is essential.

Significant advances in communication technologies are vital to keep up with this progression. State of the art 40Gb/s and 100Gb/s data transmission protocols are supported with both copper wire and fiber optics [2]. Theoretically, however, optical interconnects make a stronger contender for high speed networks due to their exceptional potential for higher bandwidth, lower latency, lower energy consumption, and scalability [3]. New fiber technologies (multi-core and hollow core fiber) have enabled up to 100 Tb/s aggregate transmission rate in a single fiber [4]. Further, several types of multiplexing technologies offer extra leeway in bandwidth capacity enhancement [5,6]. The achievement of Tb/s range bandwidth capacity is of particular significance for massively parallel computing, many fundamental physics experiments and state of the art reduced-latency internet applications, such as video surveillance, telemedicine, smart car navigation, tracking and more [7].

Although these record numbers are shown in optical fiber, many of the bandwidth enhancement techniques, such as wavelength and mode division multiplexing, are also applicable to silicon photonics [8,9], where the limits are currently being explored. Recent examples include the first demonstration of the wavelength division multiplexing (WDM) compatible silicon photonic platform, with aggregate data rates up to 60Gb/s [10] and 1x8 Mach-Zehnder WDM (de)multiplexers fabricated using a standard 90nm CMOS process [11].

While optical interconnects already comprise the backbone of modern information processing systems, low cost electronics will continue to support many important functions such as data transport monitoring, switching, modulation, forward error correction, and fault control. However, efficient data conversion between the optical and electrical domains relies upon seamless integration of multiple components, such as lasers, modulators, detectors, amplifiers, multiplexers, demultiplexers and logic. Systems assembled with many discrete components need to be further aligned and interconnected with optical fibers and copper wires. For example, a single 40 channel WDM terminal node can contain more than 100 devices and components and nearly 300 fiber coupling connections [12]. Hence, various types of losses can accrue quickly, dramatically increasing power consumption and leading to high maintenance costs for these systems. The sheer number of wires and fibers, growing in response to ever-increasing volumes of data, will soon become architecturally and ergonomically unviable. The recent U.S. Government overview of best practices for energy-efficient data centers design suggested implementation of energy efficient cooling systems, higher efficiency equipment and consolidation of components [13]. Evidently, to overcome these deficiencies we need to develop new integration platforms for efficient, scalable and
multifunctional integrated systems. One of the key elements required to enable such integrated systems is an ultra-compact, energy efficient and robust near infrared laser source.

A major driving force of optical interconnects research is device and circuit footprint reduction for scalable on-chip networks [14]. In this quest for the ultimate miniaturization, a variety of subwavelength lasers have been demonstrated [15–18], including an epitaxially grown nanolaser on silicon [19], a III/V/Si photonic crystal nanolaser [18] and a wafer bonded nanolaser on silicon [20]. We have previously shown that room temperature lasing could be achieved using metal-dielectric and coaxial sub-wavelength cavities [21–23]. These metal-based resonators are also uniquely suitable for high density integration, since this design limits cross-coupling between adjacent devices [14]. However, building a functional subwavelength laser on silicon for photonics integration still requires developing an efficient electrical injection scheme and laser-to-waveguide mode coupling.

In this paper we explore new design and fabrication approaches with the goal of enabling ever smaller hybrid III-V/Si lasers. While a number of nanoscale hybrid lasers have already been demonstrated, several problems need to be addressed for their practical implementation. In Section 2 we give a brief overview of state of the art hybrid photonic devices and integration technologies. In Section 3 we discuss our recent experimental demonstration of the III-V/Si optically pumped distributed feedback laser, targeted to improve optical efficiency in a submicron cross-section hybrid laser. In the same section we cover two main engineering issues associated with electrical injection of the hybrid DFB laser: semiconductor p-i-n stack design and device-to-waveguide coupling. Here we consider several design approaches and weigh their pros and cons for different applications. In Section 4 we describe state of the art hybrid-to-silicon waveguide coupling techniques, compare advantages and disadvantages, and propose a new low-loss coupler. Finally, in Section 5 we offer a perspective on further miniaturization of DFB lasers. In this context, we discuss various types of deeply subwavelength metal cavities and hyperbolic metamaterial architectures, which show promise for extreme footprint reduction of photonic integrated circuits (PICs).

2. Chip scale integrated photonics: state of the art

While on-chip PICs do not currently enable as much bandwidth capacity as optical fibers, they have many advantages. Firstly, they can be mass produced at a very low cost in a standard CMOS foundry, rather than assembled from multiple parts made with various expensive compound semiconductor technologies. Secondly, consolidation of as many components as possible on a single chip will improve overall efficiency of information processing networks and clean up the complexity in data centers. In particular, silicon makes a great material platform for on-chip PICs. Low optical loss, mature technology, great potential for miniaturization and an extensive library of silicon-based photonic and electronic devices make silicon photonic circuits a future technology for chip scale optical information processing.

Notable advances have been made in the industry within the past few years. In 2010 IBM announced a new CMOS integrated nanophotonics technology for dense integration of electrical and optical devices on a silicon chip. This technology enables monolithic integration of electrical and optical circuits on the same chip via the front-end of a standard 90nm CMOS line. Over several years IBM Research has developed a whole library of front-end integrated active and passive silicon devices, scaled down to the diffraction limit [24]. In 2013, Intel announced transceiver and connector modules based on silicon photonics technology, which will be able to carry 100Gb and 1.6Tb of data per second, respectively. The Intel connector can optically convert bits of information and send them through 64 optical fibers at once [25]. In 2013 Skorpios Technologies and Aurrion, reported the first III-V/SOI hybrid lasers, fabricated in a commercial CMOS foundry [26,27]. These breakthrough technologies can significantly reduce the costs of running a data center.
An emerging trend of mid-infrared PICs (wavelength range of 2-10 μm) takes integrated photonics beyond telecommunications and expands its applications to portable sensing, imaging and spectroscopy. Advancements in mid-IR photonics may greatly enhance analytical capabilities of life sciences, defense, pharmaceutical and food industries in a compact and inexpensive format. One of the difficulties this research is facing today is the strong light absorption in SiO₂ above 4 μm. The standard silicon-on-insulator (SOI) platform is sub-optimal in this wavelength range and needs to be replaced by a material transparent in the mid-IR. As such, silicon-on-sapphire or silicon-on-silicon nitride are potential candidates for CMOS compatible mid-IR PICs. The scope of this paper is limited to near-IR hybrid lasers, thereby we suggest a recent paper by Roelkens et al. [28] for further reading on mid-IR photonics.

2.1 Active optical components on silicon

An array of CMOS compatible hybrid components has been reported in the literature including electro-refractive and electro-absorptive silicon optical modulators [29,30], high performing photodetectors in silicon [31,32], germanium [33,34] and even graphene [35]. Light generation and amplification has also been demonstrated in indirect bandgap materials such as silicon and germanium, but building high performance lasers with these materials is still facing considerable complications. For example, Raman lasers require an external optical pump to trigger Raman scattering in silicon and induce Raman amplification [36]. An electrically pumped Raman laser is fundamentally attainable, but a highly complex engineering endeavor [37]. Silicon and germanium can also exhibit optical gain under tensile stress due to bandgap modification, as exemplified by recent demonstrations of electrically pumped strained germanium lasers [38,39]. However, the lasing threshold in these devices is still in the hundreds of kA/cm² range, compared to 1-3kA/cm² in III-V semiconductor laser diodes [40,41].

Most III-V compound semiconductors are direct bandgap materials with gain values often in the range of several thousand cm⁻¹ [40]. Other advantages of III-V compounds include bandgap energies that can be tuned by varying the alloy composition, as well as high carrier mobilities [42]. Unsurprisingly, III-V semiconductors remain the materials of choice when high optical gain or fast electronic response is required.

Frequently implemented heterogeneous integration solutions of III-V and silicon components are flip-chip bonding and chip-to-chip butt coupling. Both technologies are very advanced, reliable and allow submicron alignment precision. A great example of an efficient flip-chip bonded laser is the device demonstrated by researchers from Fujitsu [43]. The laser exhibited high wall plug efficiency (WPE) of 7.6%. High precision flip-chip bonding technology with exceptionally low alignment error (~0.1 μm) was a crucial factor in misalignment loss reduction.

The highest reported WPE to date (9.5%) has been achieved in a hybrid laser by Kotura (Mellanox) [44]. The Kotura design utilizes an external cavity reflective semiconductor optical amplifier (SOA), butt-coupled to a silicon waveguide Bragg mirror on SOI chip. A spot size converter is also an important part of the design and is incorporated to minimize coupling losses. This approach has proven to work very well for realization of high efficiency and high power hybrid lasers. With this cavity design (reflective SOA and waveguide mirror) and device-to-waveguide coupling architecture, Oracle has reported a butt-coupled laser with waveguide coupled power of 20mW, tuning range of 8nm and 35nm, depending on tuning mechanism, and WPE of 7.8% [45].

Flip-chip bonding and butt coupling are amongst the best technologies to achieve the record device performance when the footprint is not a concern. However, another approach is required when the component features are deeply sub-micron. In this case, monolithic integration of as-grown III-V and Si materials, followed further by processing of III-V/Si...
composite material as a single monolithic structure, is naturally a better choice. The main advantage of monolithic integration is that alignment can be avoided altogether.

Two fundamentally different approaches to monolithic integration have emerged in pursuit of merging III-V’s and silicon: epitaxial growth and wafer bonding. Strong lattice mismatch between silicon and III-V compounds presents a great technological roadblock to the former [46–48]. Despite this, several as-grown III-V/Si lasers have been demonstrated including the recently reported first electrically pumped edge-emitting III-V nanowire laser on silicon [19,49,50]. The alternative approach, wafer bonding, has yielded the best results so far, both in terms of scalability and laser performance, which will be discussed in greater detail in the following section.

Among many types of lasers to be developed for the new generation integrated chip scale photonic circuits, DFB lasers have drawn particular interest in the research community. Because Bragg gratings allow a limited phase window for constructive interference, DFBs provide extremely stable, single mode, narrow linewidth operation. Such signals can propagate in optical fibers or waveguides with minimal dispersion and noise. In optical communications, this translates into preserving signal integrity over long propagation distances. The wavelength stability can further be reinforced with single or multiple quarter-wave shifted cavity designs [51]. Additionally, the emission frequency of semiconductor DFB lasers can be tuned via temperature modulation or electrical injection [40].

The first monolithically integrated III-V/Si microdisk laser was demonstrated by Rojo Romeo et al [52]. The authors used molecular wafer bonding to create the III-V/SiO$_2$/Si composite with ~1.2ðm SiO$_2$ mediating layer. At the same time, Fang et al. [53] reported the III-V/Si evanescent laser. In this case the optical mode propagates in the silicon waveguide with its evanescent tail interacting with the III-V slab. The authors used plasma assisted wafer bonding, a type of direct hydrophilic bonding. This was an important milestone on the way to chip scale integrated photonic circuits, as the direct contact between III-V and Si enabled easy, low loss mode coupling between active and passive circuit elements, as well as CMOS compatibility for part of the fabrication process. This work was shortly followed by demonstrations of other types of evanescent devices and an entire evanescent photonic link with lasers, modulators and photodetectors [54–56]. Some of the hybrid devices are already on their way to commercialization.

The latest works on wafer bonded hybrid lasers include a BCB bonded DFB [57], a tunable hybrid laser [58], an integrated four-wavelength laser array [59], a sidewall modulated DFB [60], a microlaser [61], a nanolaser [20] and a slotted feedback laser [62]. Recently Santis et al. [63] proposed hybrid cavities as a way to dramatically reduce linewidth in semiconductor lasers by limiting spontaneous emission noise. These works use varying monolithic integration approaches, which we will discuss in the following section.

2.2 Wafer bonding methods

All existing wafer bonding techniques can be roughly divided into two broad classes: direct and indirect. Direct methods rely on molecular forces between the two materials. The main advantage of direct methods is the immediate vertical proximity between the III-V and silicon layers, which allows the composite structure to be treated as a single wafer during fabrication and hybrid device design. Atomic flatness and pristine condition of both surfaces are imperative for direct methods to work [64]. Pressure [65] or thermal treatment [66,67] (or both) are usually applied to assist molecular-level interactions. Hydrophilic [64,68] and hydrophobic [65,69] bonding are examples of the direct bonding technique. In hydrophobic bonding, all native oxides must be stripped to leave both surfaces hydrogenated, and bonding is carried out in vacuum, under pressure at room or elevated temperatures [65,67,69]. Hydrophilic bonding relies on Van der Waals forces to facilitate attraction between the surface species. Either wet chemistry or plasma treatment can be used to make the surfaces
hydrophilic. After Van der Waals bonding, the composite structure typically undergoes thermal processing to encourage covalent bond formation.

Indirect methods use a third mediating material between the materials to be bonded. Metal-based [70–72] anodic [73] and adhesive bonding methods [74,75] are all indirect methods. The indirect approach helps to circumvent the problem of lattice mismatch, surface roughness and poor planarity.

Metal-based bonding techniques are perhaps the oldest and most established to date. The oldest, thermocompression bonding [70], relies on atom diffusion between different metals at elevated temperatures. Another popular indirect method, eutectic bonding, is similar to soldering and based on metal alloy formation [71,72,76]. Eutectic bonding uses lower temperatures than thermocompression, but may have poor bond stability. It is also incompatible with CMOS processing because of ion diffusion.

Anodic bonding is normally used for bonding semiconductors to borosilicate glasses. Strictly speaking, anodic bonding does not require an extra material layer, but one of the materials (typically, the glass cathode) must be doped with high mobility charge carriers [67,73]. This can have an adverse effect on electronic device performance and, thus, is not a good choice for CMOS integration.

Some of the popular wafer bonding adhesives include benzocyclobutene (BCB) by Dow corning, SU-8 polymers [74], and hydrogen silsesquioxane (HSQ) [75]. Typically, adhesive wafer bonding is carried out at lower temperatures than most other wafer bonding techniques, but the downside is low temperature stability of the bonding interface and poor surface quality.

In the rest of this review, we will focus on the direct bonding approach of III-V to silicon on insulator (SOI).

3. Sidewall modulated III-V/SOI DFB laser

3.1 Optically pumped laser

In this section we briefly discuss our recently reported optically pumped III-V/Si DFB laser [60]. We implemented self-aligned sidewall modulated Bragg gratings for optical feedback to maximize the interaction between the electric field of the mode and the available gain in the structure. This approach can help to reduce lasing threshold and/or physical size of the device. In our work we showed lasing in a 100μm long hybrid grating with sub-micron waveguide cross-section (Fig. 1(a)). The waveguide sidewall modulation is achieved by varying its width with period Λ along the mode propagation direction, with w1 and w2 widths corresponding to the wide and narrow sections of the guide. We apply the plasma-assisted wafer bonding technique, followed by self-aligned fabrication [66,68] for scalable, simple and alignment-free fabrication. Our choice of wafer bonding method was limited by our low temperature process requirement (below 400 °C) and the reliance of our cavity design on direct III-V/Si bond configuration.

In the following, we examine only the fundamental TE-like mode of the composite III-V/Si waveguide. This is justified by our use of multiple quantum well (MQW) InGaAsP gain material for the device, where the TE-like mode experiences significantly higher gain than the TM-like mode [77]. In our finite-element method (FEM) analysis of such waveguides, we consider the gain/mode overlap of a bulk InGaAsP/Si composite waveguide for computational simplicity (Fig. 1(b,c)). The simulations show that the fundamental TE-like mode is evenly distributed between the silicon and III-V layers. Quantitatively, this is described by a modal confinement factor in the gain, Γ_{III-V}, and silicon, Γ_{Si}, that are both close to 0.5.

It is appropriate to neglect coupling to higher order modes and only consider coupling of the forward propagating mode to the counter-propagating mode of the same order and polarization. However, in our case, κ, makes a weighty contribution to the total κ, since the E_z
component is not only large, but also strongly overlaps with the sidewall grating. Based on FEM simulations and the Coupled Mode Theory (CMT) we estimate the total coupling coefficient is ~85cm\(^{-1}\), taking into account the large \(\kappa\) and fabrication imperfections. Further CMT analysis of a grating with this value of \(\kappa\) and a 100\(\mu\)m length yields a threshold gain of ~400cm\(^{-1}\). The material gain in multiple quantum well (MQW) media theoretically reaches ~6000cm\(^{-1}\) [78], which is sufficient to compensate for the lower gain/mode overlap in our MQW InGaAsP/Si composite waveguide.

Fig. 1. (a) Schematic of a sidewall modulated DFB laser, top view; Simulated (b) E\(_x\) component and (c) E\(_z\) component of the fundamental TE-like mode for a 500nm wide and 550nm tall III-V/Si waveguide with 250nm silicon layer, 300nm InGaAsP layer; (d) Light-light curve of a fabricated optically pumped device (the same data in logarithmic scale – bottom right inset, SEM image of the hybrid grating is on the upper left inset).

Optical measurements on the DFB structures were carried out on a standard microphotoluminescence setup with a 1,064nm nanosecond pulsed fiber laser. We observed the single mode lasing peak at 1,515nm wavelength with linewidth below the monochromator resolution limit of 0.35nm. From light-light measurements (Fig. 1(d)) we extracted the threshold peak pump intensity to be around 530W/mm\(^2\). To conclude this section, we note that the flexibility of a sidewall modulated grating design can also enable the development of low-threshold hybrid DFB lasers, albeit at the expense of a larger physical size. Work on an electrically pumped version of the laser involves additional challenges, as we discuss in the following section.

3.2 Electrically pumped laser

The first electrically pumped hybrid lasers were based on the InAsP microdisk [52] and AlGaInAs-silicon evanescent designs [53]. Several other approaches for a better III-V/Si device-to-waveguide coupling were developed shortly after these first demonstrations [79]. Today, almost a decade later, the hybrid platform has become essential to the development of photonic integrated circuits providing elements on a chip such as: optical amplifiers, 2R regenerators, modulators, photodetectors, etc [80]. This year an efficient electrically pumped DBR hybrid laser was also demonstrated by Duan, et al [81].

As described in section 3.1, in the case of the optically pumped hybrid DFB laser, the active III-V layer is directly bonded to the silicon layer and the mode of the III-V/Si composite waveguide is almost equally confined to the silicon and III-V layers. For electrical
carrier injection, a p-i-n heterostructure must be incorporated into the III-V epitaxial layers. In a p-i-n heterostructure the active region is intrinsically doped, while top and bottom contact layers, InGaAsP and InP, are p- and n-doped, respectively. Figure 2(a) schematically depicts the semiconductor stack after wafer bonding. The top and bottom InGaAsP layers are heavily doped (1x10^{19} \text{cm}^{-3}) for low resistance ohmic contacts. The InP cladding layers have a lower doping level (1x10^{18} \text{cm}^{-3}) to reduce optical losses from impurities, as a small portion of the mode propagates within these cladding layers. The n-doped bottom layer (InP-n and InGaAsP-n in Fig. 3(a)), is hereafter referred as bonding layer.

The bonding layer thickness is one of the most important optimization parameters since it affects the gain/mode overlap. Generally, a higher gain/mode overlap may be achieved with a thicker III-V layer stack. However, the mode propagation losses in the doped layers and complexity of the mode coupling to a silicon waveguide are the challenges associated with thick layers. To illustrate this problem, we consider two extreme cases in this section: a III-V stack with a very thick (325nm) and a very thin (40nm) bonding layer. The choice of a specific design depends on desired functionalities of the device.

Figure 3(b) shows the schematic diagram of our cross-sectional geometry. Simulation results for the structures with the thick and thin bonding layers are presented in Fig. 2(c) and 2(d) for comparison. In both cases, the width of the III-V region is set to be 500nm to ensure that only the fundamental mode is excited. The width of the silicon waveguide is 1200nm and its thickness is 250nm. To reduce radiation losses, a 130nm layer of SiO\textsubscript{2} covers the sidewall of the III-V region. Figure 2(c) and 2(d) show the spatial mode distribution for stacks with the thick and thin bonding layers, respectively. The bonding layer thickness is InGaAsP/InP 125/200nm in Fig. 2(c) and InGaAsP/InP 20/20nm in Fig. 2(d). Evidently, a thicker bonding layer yields higher gain/mode overlap and lowers the overlap with the silicon waveguide. In this case, the confinement factor $\Gamma_{\text{III-V}}$ for the gain region is 0.17 while that for the silicon waveguide, $\Gamma_{\text{Si}}$, is only 0.07.

The spatial distribution of the electromagnetic field for a thin bonding layer is shown on Fig. 2(d). We observe that the mode only partially extends from the silicon waveguide into the gain region. In this case, the confinement factor $\Gamma_{\text{III-V}}$ is only 0.101 while for the silicon waveguide, $\Gamma_{\text{Si}}$, is 0.407. The advantage of the thin bonding layer is that the mode is strongly confined in silicon, which favors the mode coupling to a passive silicon waveguide. Also, as reported by C. T. Santis, et al. [63], if the energy is generated and stored in the same lossy III-V material (the gain media and the doped layers), there is an excessive spontaneous emission noise degrading the laser coherence, so the laser may not meet the requirements for phase-coherent modulation. The disadvantage of the thin bonding layer is that the low $\Gamma_{\text{III-V}}$ can lead to a higher threshold current density compared to the thick bonding layer and high $\Gamma_{\text{III-V}}$. Low
threshold current helps to reduce power consumption and avoid heating. Thermal effects can introduce drift of the emission peak, reduce the internal quantum efficiency and device reliability, as well as accelerate its degradation [82]. Besides optimization of electrical and optical properties of the semiconductor structure, it is necessary to couple these modes to a silicon waveguide with minimal optical loss. To address this issue we propose tapered waveguides for low loss mode coupling.

3.3 III-V/Si to silicon waveguide coupling

Efficient light routing between passive and active devices in a photonic chip requires a coupler, where the mode is pulled into a silicon waveguide from the active section. A schematic of three different taper geometries are shown in Fig. 3. Design I is a three etching level taper used by Heck et al [80]. Design II is a conventional taper used by Lamponi et al. [83], and Design III is a conceptual 3D taper waveguide. Each of these tapers couples the mode from the III-V region to the silicon waveguide adiabatically to prevent excitation of other transverse modes.

We present Designs I and II as examples of taper couplers, since they have been previously shown to exhibit high transmission efficiency due to low modal impedance mismatch [80,83–85]. In Designs I and II the silicon waveguide widths are shorter than that of the III-V. This is achieved by first fabricating the silicon waveguides on a SOI platform, then bonding them to the III-V stack and executing top-down fabrication on the entire III-V/Si stack. To illustrate the modal behavior in different regions of the tapered waveguides, we use the thicker bonding layer in these examples.

Taper Design I consists of three etching level tapers where each material layer (p-cladding, gain media and n-cladding) are tapered with different taper lengths. In our simulations the tapered tip widths are equal to 400nm but this can vary from layer to layer. The silicon waveguide thickness is fixed at 1.2μm to demonstrate that the spatial mode distribution changes during the coupling process. Note however that the silicon waveguide can be tapered in the opposite direction prior to wafer bonding of III-V and Si to increase the coupling efficiency [80]. Figure 3(a)-3(c) show the evolution of the spatial mode distribution along the tapered waveguide as the mode is pulled into the silicon waveguide. The optical mode initially is localized in the gain media where laser light is generated (Fig. 3(a)). With tapering of the III/V, the optical mode gradually transfers to the silicon waveguide. In the last step (Fig. 3(c)), almost no modal energy remains in the gain media. The total length plays an important role in this design. Park et al. used a three etching level taper with the total length of 80μm in their work on the hybrid AlGaInAs-Si preamplifier and photodetector [84]. They measured the taper losses of 0.5dB per transition region. Increasing the total taper length to 160μm, Kurczveil et al. [85] reduced the losses to 0.3dB per transition region and applied the tapers on an integrated hybrid silicon multiwavelength asymmetric waveguide grating laser.

In the second approach all three layers have the same taper length and tip width, as illustrated in in Fig. 3 (Design II). All dimensions are identical to Design I, unless noted otherwise. The spatial mode distributions for the different cross-section widths are shown in Figs. 3(d)-3(f). The evolution of the mode from the III-V to silicon waveguide is similar to Design I. In this configuration the silicon waveguide is also tapered on a pre-bonding fabrication step. Design II is [54] extremely sensitive to the tip width. If the tip width is not sufficiently small, the optical mode cannot be pulled into the silicon waveguide efficiently. Fortunately, a larger silicon waveguide thickness allows a more efficient coupling with larger width III-V tapers [66]. With this design, Lamponi et al. reported 90% coupling efficiency in a 100μm long taper with a 400nm taper width in the III-V region [83]. This taper design was used to demonstrate a tunable hybrid silicon laser directly modulated at 10Gb/s [86].
We propose an alternative coupler design concept, which can be accomplished solely with top-down fabrication of 3D tapered waveguides, illustrated in Fig. 3 as Design III. This coupler is adiabatically tapered both along its length and its width, which is expected minimize scattering losses at the tips/edges of the tapered waveguide and thus improve coupling efficiency. The spatial mode distributions for the different cross-sections of Design III are shown in Figs. 3(g)-3(i). A mode profile for a thin (40nm) bonding layer is shown on Fig. 3(i) and for a thick (325nm) bonding layer in Fig. 3(j). Note that the mode pulling into the silicon layer can take place over a relatively large range of bonding layer thicknesses.

Figure 4 shows the 3D-FDTD (Finite-difference time-domain) simulation of the 3D taper. All dimensions are identical to Design III in Fig. 3 and the taper length is 15μm. In the simulation, a light pulse is launched inside the gain media and propagates toward the right side. After traveling through the 3D taper, the pulse is gradually pulled into the silicon waveguide. We have extracted and calculated the coupling efficiencies for the coupling between the gain media and the silicon waveguide. Note that the coupling efficiency is defined as the ratio between the output power into the Si waveguide and the power injected into the gain media.

In Fig. 4 we compare four different coupler structures in terms of their coupling efficiency versus signal wavelength: a coupler with a (1) thick bonding layer and 2D taper; (2) thick bonding layer and 3D taper; (3) thin bonding layer and 2D taper and (4) thin bonding layer and 3D tapers. Figure 4(b) shows that both structures with a thin bonding layer, regardless of the taper type, have coupling efficiencies higher than those of the structures with thick bonding layers. Both structures with a thin bonding layer are comparable in their coupling efficiencies, reaching 90% for longer wavelengths. Despite the lower overall efficiencies for structures with the thick bonding layer, the thick 3D taper can be extremely beneficial to
coupling efficiency, which is apparent from Fig. 4(b). One also can notice that the difference between 2D and 3D tapers with thick bonding layers are significant. Nevertheless, when designing the tapers, optical loss, conductivities and current injections also must be considered for an optimal laser/coupler system design. For example, a thicker bonding layer would increase the modal confinement within the gain media and thereby reduce the lasing threshold. Both the shape and dimensions of the taper and bonding layer may be used to optimize laser performance depending on the system requirement.

Another advantage of our 3D taper with thin bonding layer is the taper length. Since the mode transfer is more efficient in Design III, which is qualitatively shown in Fig. 3(g)-(j), the taper length can also be significantly reduced. With a thin bonding layer and 3D taper, the taper length is much shorter than that used in Design I (80-160μm) [79] and Design II (>100μm) [82]. Figure 4(c) shows the coupling efficiencies of varying length 3D tapers and thin bonding layer. The coupling efficiencies are almost identical for taper lengths ranging from 15μm to 20μm. This window is wide enough to have good fabrication-error-tolerance. The average coupling efficiencies are above 80% and reach 90% for certain wavelengths in the 1.4-1.5μm range. These efficiencies are comparable with the reported result for Design II [82]. It is worth noting that lengths above 100μm are preferred to get robust coupling in Design II taper, while the same result can be achieved in Design III taper with a length 5 times shorter.

To verify the feasibility of the Design III, we performed ion-milling process using test silicon and III-V/Si structures. The beveling effect, shown in the scanning electron microscope (SEM) pictures (Fig. 5), is achieved through an extended (30-50 min) O2 reactive
ion etch (RIE) treatment. For this processing we use Trion RIE tool with elevated O₂ gas flow and chamber pressure of 100sccm and 100mT, respectively. The RF power was set to 150W. SEM images of a silicon waveguide and a test composite Si/InGaAsP structures after 45 minutes of RIE are presented in Fig. 5 (a and b), respectively. This process employs concentrated oxygen plasma to achieve the ion-milling effect. From Figs. 5(a, b) InGaAsP appears to respond to the treatment faster than silicon due to the difference in mechanical properties. Since this process is physical, rather than chemical, it may be possible to replace O₂ gas with Ar, for example.

In conclusion, we propose a new approach to optical mode transfer from the gain medium to Si waveguide with reduced footprint and reasonable coupling efficiency. We also find that the bonding layer thickness and taper shape play essential roles in optimization of coupling efficiency. Our simulation results suggest that a thin bonding layer in combination with 3D taper can make mode transfer more efficient and very compact. We would like to point out that there is no preferential choice between Designs I and II, since their properties are quite similar in terms of threshold current, power consumption and coupling efficiency [80,81,85], while the performance of Design III taper coupler remains to be experimentally tested.

4. Perspective: pushing the footprint of DFBs to the nanoscale

While narrow linewidth and frequency stability are arguably the most important attributes of DFB lasers, future dense chip-scale integration of DFBs with photonic integrated circuits will benefit from size reduction. In the following perspective, we introduce concepts from nanoscale resonant devices to assess the possibility of DFB lasers with extremely small footprints. For simplicity we assume that bonding of such lasers may be achieved using techniques discussed in earlier sections.

The cavity $Q$ characterizes the photonic “transit” time, or duration that a photon will stay in the cavity. Generally, the $Q$ is expressed in terms of cavity loss channels, $Q^{-1} = Q_{rad}^{-1} + Q_{dissip}^{-1} + Q_{other}^{-1}$, including radiative, dissipative, and all others denoted by $Q_{rad}$, $Q_{dissip}$, and $Q_{other}$, respectively [63]. To achieve a narrow linewidth, the $Q$ must be very large. For small cavities, with dimensions on the order, or even smaller, than the freespace wavelength, maintaining a large $Q_{rad}$ is feasible only with the introduction of metallic constituents. The metal however reduces $Q_{dissip}$, which indicates an inherent tradeoff. Research has shown that the introduction of a thin, low-index dielectric layer between the metal cladding and gain region, can greatly increase $Q_{dissip}$ while still reaping the benefits of a high $Q_{rad}$ [21,87]. This dielectric “shield” layer enabled room-temperature operation of the first fully sub-wavelength (in all 3 spatial dimensions) semiconductor laser, which operated near 1550nm [88]. The
shield layer has also proven important in subsequent wavelength-scale lasers pumped via electrical injection, including up to room-temperature [89,90].

State-of-the-art, subwavelength, semiconductor lasers are generally surface-emitting, and, therefore, are not easily integrated with waveguides and other on-chip devices. However, hyperbolic metamaterials consisting of III-V compounds offer a potential means of creating integrated, in-plane subwavelength semiconductor lasers.

Hyperbolic metamaterials (HMMs) are periodic composite media with deeply subwavelength layers of metal and dielectric that exhibit unique physical properties [91]. In particular, HMMs support modes, in the ideal limit, with arbitrarily large spatial-frequency. Physically, the transmission through HMMs is due to strong coupling of surface-plasmon polaritons (SPPs) at adjacent metal-dielectric interfaces, which lead to the formation of volume plasmon polaritons that transmit energy in the direction normal to the interfaces [92]. Because of the high-spatial frequency modes supported by HMMs, waveguides with extremely small cross-sections can be envisioned. By substituting the passive dielectric constituent with a III-V semiconductor, one can introduce optical gain to offset dissipative losses caused by the presence of metal. For applications requiring telecommunication frequencies, either noble metals or transparent conducting oxides can be used for the metallic constituent. In the limit of effective medium theory, the combination of silver and InGaAsP, under moderate pumping levels, can lead to complete loss compensation for a propagating waveguide mode [93].

A schematic of an in-plane HMM waveguide is shown in Fig. 6(a). The waveguide height and width, \( h \) and \( w_1 \), can be simultaneously deeply subwavelength. For example, the cylindrical silver/InGaAsP HMM waveguide of [93] supports lossless propagation of the fundamental TM\(_{01}\) mode in a radius range of 50 to 150nm, for moderate pumping levels, and metal fill fractions between 30 to 70%. In the rectangular waveguide of Fig. 6(a), the TM\(_{11}\) mode is the fundamental mode. Assuming a square geometry for simplicity, the waveguide dimensions of \( 50nm < h = w_1 < 200nm \) enable lossless propagation in the quasi-static effective medium limit.

The extension of a waveguide-integrated HMM exhibiting lossless transmission to one with lasing requires a mechanism to provide positive feedback. This might be achieved through a periodic modulation of the waveguide width as shown schematically in Fig. 6(b). The modulation of the waveguide width has a period on the order of the emission wavelength, which is much greater than the deeply subwavelength periodicity of the HMM. Due to the
high-\textit{k} modes supported by the HMM, the widths of the narrow and wide sections of the waveguide, \( w_1 \) and \( w_2 \), respectively, can both be less than 100nm. This enables densely packed waveguides for WDM applications.

A number of challenges exist concerning the realization of a nanoscale hybrid-DFB. These include deposition of metal into the nanostructured III-V compound, as well as design of electrical contacts. If a noble metal is used as the metal, the thickness of the individual metal layers should be <30nm to enable coupling between adjacent layers. This pushes the limit of physical deposition techniques, such as electron beam evaporation and sputtering [94]. On the other hand, if a transparent conducting oxide (TCO) is used for the metal, the individual metal layers can be significantly thicker due to the much larger skin depth of TCOs [95]. Highly conformal thin films of TCOs may be deposited via atomic layer deposition (ALD), which is a monolayer-at-a-time chemical technique originally developed for oxides [95]. Deposition of noble metals via ALD is also feasible; however, ALD of single-element materials is inherently more difficult than ALD of compounds [96].

While an in-plane HMM based on noble metals may be challenging to realize in practice, we note that the proposed device concept is only one of many possibilities. We have suggested that reduction of DFB dimensions for greater density of integration may be achieved by modulated active HMM waveguides. While the quality factor of such devices will suffer due to the presence of metal, the footprint will be greatly reduced compared to state-of-the-art DFB lasers.

5. Conclusion

We have reviewed hybrid III-V/Si DFB lasers for their use as optical interconnects. Our discussion has included a review of optically pumped hybrid DFB laser with a post-bonding fabrication process. We have also discussed design considerations for electrically pumped DFB lasers, including the bonding layer thickness and waveguide tapering. Finally we have offered a perspective on the potential use of active metamaterials for extremely compact, nanoscale DFBs.

Acknowledgments

This work was supported by the Office of Naval Research Multi-University Research Initiative (N00014-13-1-0678 and N00014-14-1-0505), the National Science Foundation (NSF) (ECCS-1405234, ECCS-1229677, CBET-1445158), the NSF Center for Integrated Access Networks (EEC-0812072, Sub: Y502629), the Defense Advanced Research Projects Agency (N66001-12-1-4205), and the Cymer Corporation.