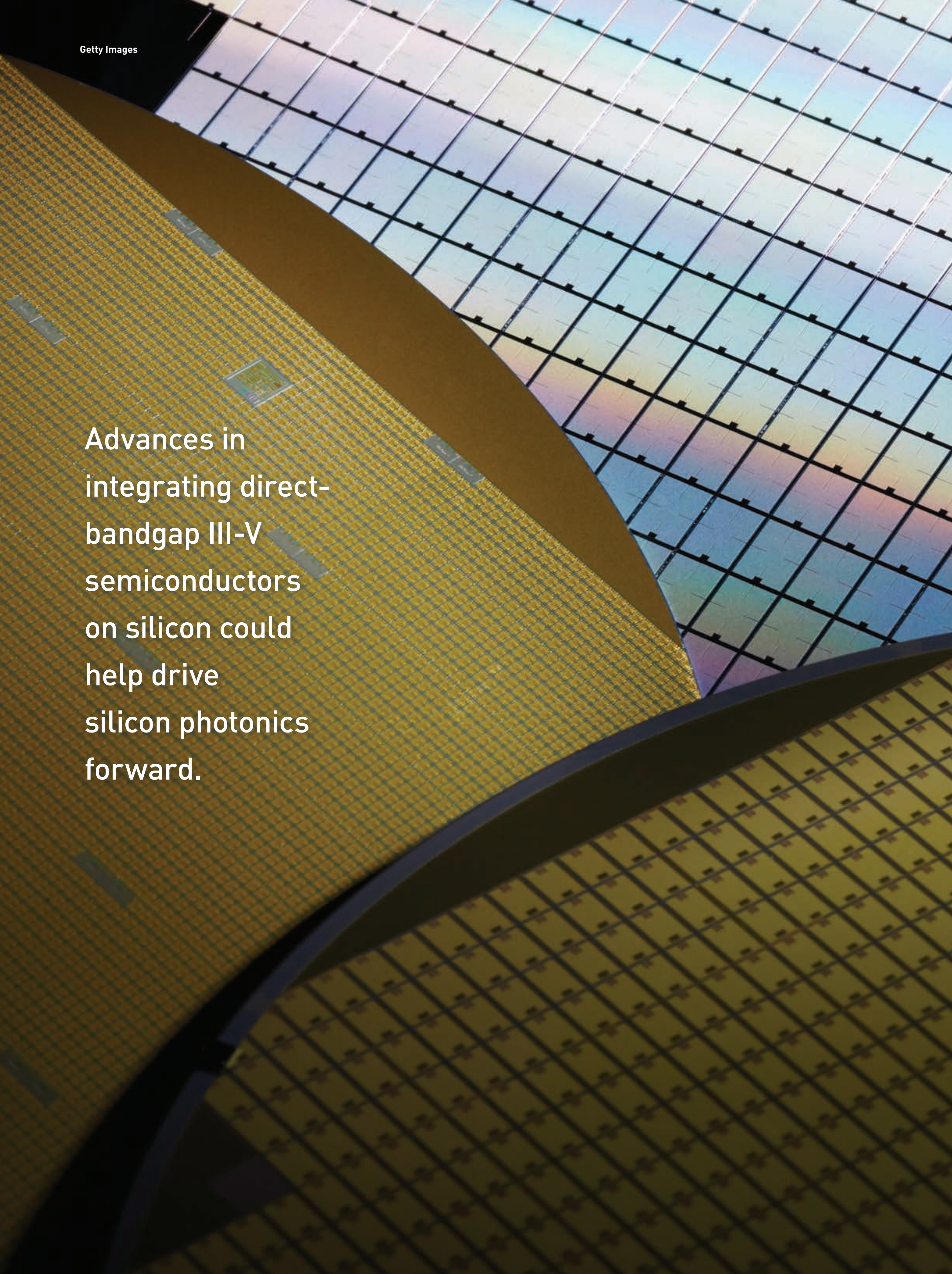
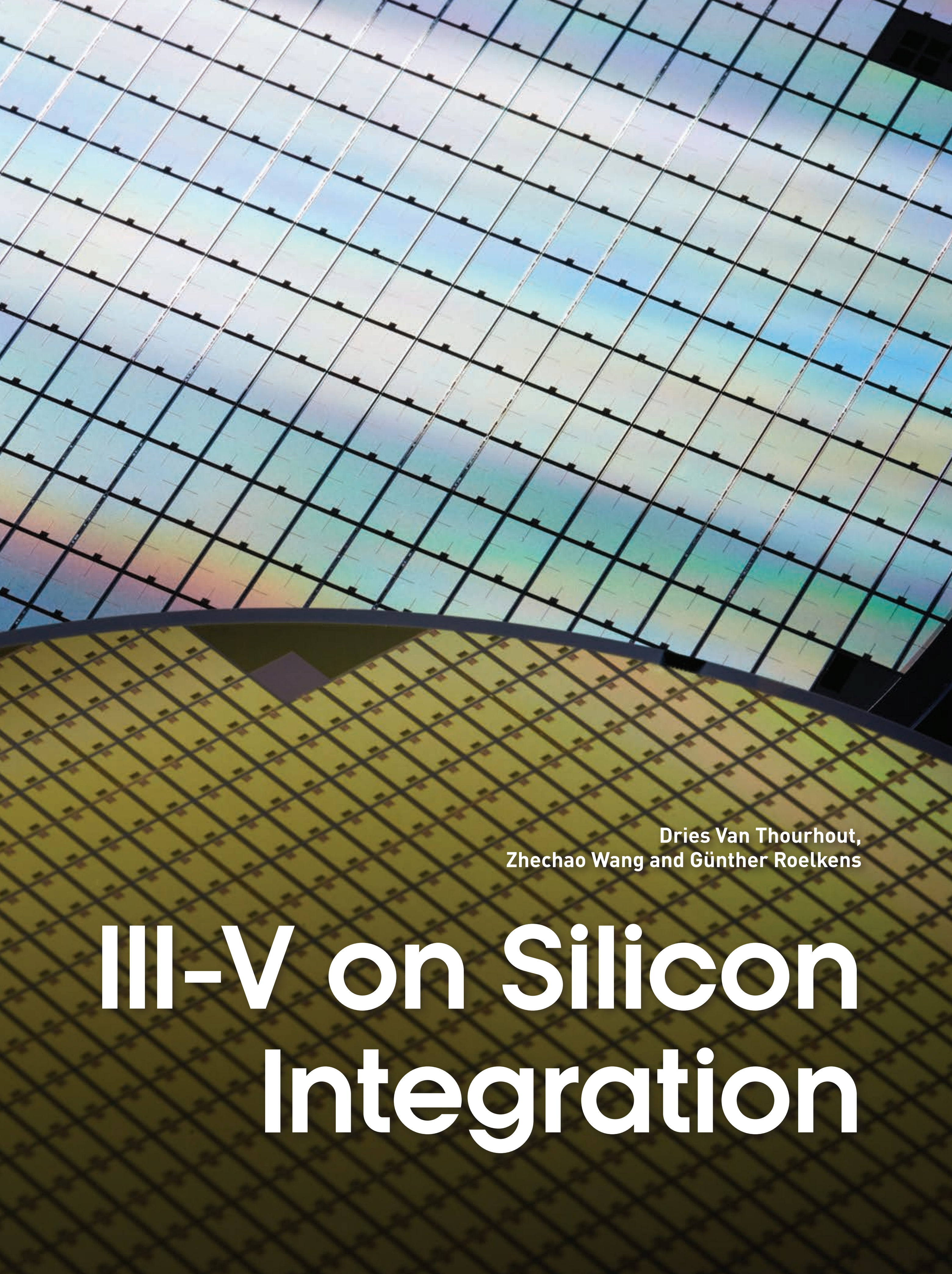


Getty Images

Advances in integrating direct-bandgap III-V semiconductors on silicon could help drive silicon photonics forward.



Dries Van Thourhout,
Zhechao Wang and Günther Roelkens

III-V on Silicon Integration

Over the last few years the research community has made tremendous strides toward realizing fully integrated laser diodes on silicon.

Silicon has long offered promise as the ultimate platform for realizing compact photonic integrated circuits (PICs). That promise stems in part from the material's properties: the high refractive-index contrast of silicon allows strong confinement of the optical field, increasing light-matter interaction in a compact space—a particularly important attribute for realizing efficient modulators and high-speed detectors. Even more important, however, silicon photonics relies on materials and processing techniques already highly developed by the silicon CMOS industry. This means it can leverage the best tools and processes available, without the need for high additional capital investments, raising the potential for high performance at low cost.

Thus far, applications in telecom and data communications have driven most industrial development in silicon photonics, though research is also under way in biosensing, spectroscopy and more exotic domains such as quantum optics and optomechanics. Silicon-based PICs have become widely available both for large industrial firms, through several commercial wafer foundries, and for small- and medium-sized enterprises (SMEs) and universities, through multiproject wafer services such as Europractice and IME. The AIM Photonics project in the United States also promises new development in the techniques and technology for silicon photonics.

Yet amid all of that progress, the field has faced a big stumbling block: the lack of an integrated laser source. Thus far, silicon-photonics applications have had to rely on external laser sources that feed the optical chip through optical fiber, or on flip-chip integration of separately fabricated laser diodes. Neither of those approaches is scalable to very large wafer volumes or to more complex laser designs.

Over the last few years, however, the research community has made tremendous strides toward realizing fully integrated laser diodes on silicon, both through wafer-bonding techniques that integrate direct-bandgap III-V epitaxial materials into prefabricated silicon circuits, and through direct epitaxy of III-V semiconductors on silicon. The latter approach, investigated for decades without much progress, has lately seen substantial advances in overcoming the large lattice mismatch between silicon and III-V semiconductors such as GaAs and InP. Below, discuss at both approaches, including some specific examples drawn from work by our own group.

Integration via wafer bonding

Wafer-bonding techniques constitute the most mature approach for integrating III-V materials on silicon. As shown in the diagram below, the approach begins with a preprocessed silicon-photonics wafer already containing waveguides, optical filters and possibly active elements such as modulators and detectors, which has been planarized by chemical-mechanical polishing in a CMOS fab. Dies cut from a III-V wafer—obtained from a separate foundry, and containing suitable gain layers and a sacrificial etch "stop" layer—are next bonded on top of the silicon waveguides, with the optically active layers down. The substrate is removed down to and including the sacrificial layer, at which point the wafer can be further processed using standard planar processing techniques, including high-accuracy lithography. Thus the lithography process, rather than that of a less-precise pick-and-place process, determines the alignment of the fabricated lasers with the silicon waveguides.

Fabricating the laser typically involves etching the laser mesa, including structures for coupling the light to the silicon waveguides, for passivation, and for defining *n*- and *p*-type metal contacts. For lasers, which are evanescently coupled to silicon waveguides, the bonding process used must ensure that the thickness of the bonding layer is sufficiently small and well-controlled; that the layer is sufficiently transparent; and that it is applied at a temperature low enough to avoid influencing the quality of the bonded III-V semiconductor material and creating excessive strain due to differential thermal expansion between the III-V and the silicon substrate.

The most popular bonding approaches use either oxide or benzocyclobutene (BCB), a polymer provided by Dow Corning (USA), as the bonding agent. The use of oxide bonding media requires the bonded substrates to be strictly planar, and measures to allow

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H_2O outgassing. The BCB method (used in our own lab) is more tolerant to non-planar substrates, and can reliably deposit bonding layers as thin as 30 nm.

One drawback of BCB is a lower thermal conductivity than silica; in practice, however, other factors than this thermal-conductivity difference, such as the buried oxide layer of the silicon-on-insulator (SOI) wafer, tend to dominate the thermal impedance of the actual fabricated devices. (Most of the design concepts that we talk about in the following paragraphs are independent of the exact bonding method used.)

Building up integrated devices

In creating integrated III-V–silicon devices from wafer bonding, our lab uses an efficient optical-amplifier structure as a key building block. In the amplifier's central part, an active layer of a ridge-type III-V waveguide, typically containing 6 to 9 quantum wells, strongly confines the light; at either side, an adiabatic taper efficiently couples the light into a 400-nm-high silicon waveguide. This taper imposes an estimated loss of less than 1 dB, and—more important for complex laser designs—it exhibits very low spurious reflections that could affect laser performance.

A big advantage of the hybrid-integration platform lies its inherent hermeticity. The amplifier is sealed from the environment during the process, on wafer scale. This allows cheaper packaging approaches, avoiding the need for expensive hermetically sealed boxes. The optical amplifier can thus be used as a modular component, and combined with suitable feedback structures—defined with high accuracy in the silicon waveguide layer—to create a whole series of different lasers with specific functionalities. Some examples include:

Distributed-feedback (DFB) lasers. Integrating the amplifier on top of a DBR-grating allows creation of DFB lasers with well-controlled wavelengths and high side-mode suppression ratios—and with threshold currents lower than 10 mA and output powers greater than 10 mW. The high optical confinement in these hybrid III-V–silicon DFB lasers makes them

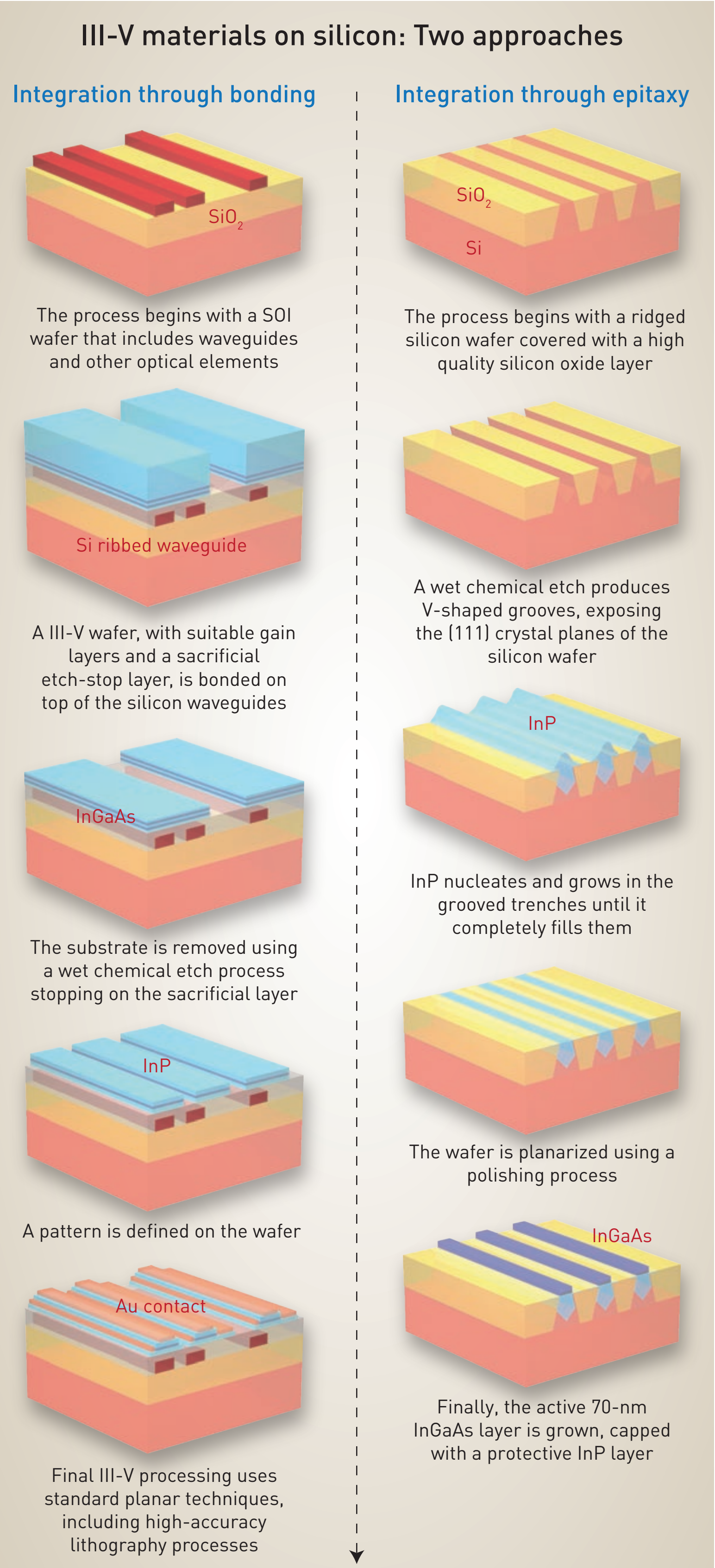


Illustration by Phil Saunders

A hybrid III-V-on-silicon mode-locked laser offers a prime example of the power of the emerging integration platform based on wafer bonding.

very well suited for high-speed direct modulation (that is, at rates above 40 Gb/s).

Tunable microring lasers. Our lab, along with others, has demonstrated widely tunable lasers in which the amplifier is integrated with two silicon microring resonators (serving as wavelength filters) with slightly differing radii that can be thermally adjusted. That adjustment ability allows tuning across a wavelength range of more than 40 nm, exploiting the so-called Vernier effect (which achieves tuning through relative adjustment of the slightly differing comb-like transmission spectra of both ring resonators).

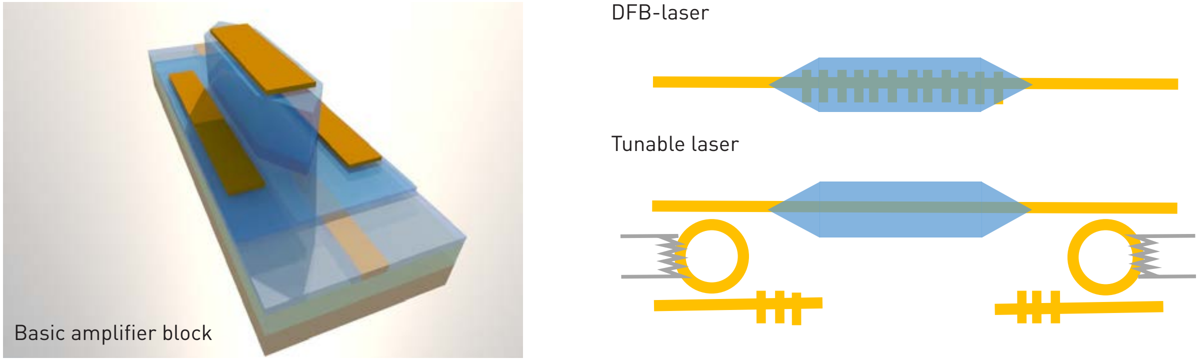
Multifrequency lasers. Combining multiple amplifiers with a wavelength multiplexer allows fabrication of very compact multifrequency lasers.

What makes bonding-based hybrid integration truly powerful is that readily extends to other materials. Such an approach has allowed our lab to demonstrate mid-infrared devices, such as integrated multichannel spectrometers operating at wavelengths up 4 μm that use antimonides as the active material; DFB-lasers operating at 2.3 μm that rely on InP type-II active regions; and 850-nm vertical cavity surface emitting lasers (VCSELs) using GaAs-based active materials. And recent research toward a "transfer printing" approach to bonding could make the process even more efficient and cost effective in the future (see sidebar on p. 37).

Case study: A mode-locked laser

A hybrid III-V-on-silicon mode-locked laser recently developed in our lab offers a prime example of the power of the emerging integration platform based on wafer bonding. Such lasers have attracted particular current interest for applications in spectroscopy, which require a set of narrowly spaced laser lines across as wide as possible of a bandwidth. Achieving that combination in the past has typically relied on optical sources such as bulky fiber lasers or solid-state lasers. The integrated devices demonstrated thus far, mostly of which have relied on monolithically integrated platforms in III-V semiconductors, have suffered from relatively large losses in the long external cavity required to reach a sufficiently narrow spacing of the longitudinal modes.

In the hybrid-integration approach we have developed, by contrast, the silicon waveguides that make up the external cavity are processed independently from the III-V amplifier, and losses can be as low as 0.7dB/cm. These mode-locked laser lasers consist of a 40-μm-long saturable absorber, an 800-μm gain section and a 37.5-mm-long external cavity, completed with a



From wafer bonding to integrated lasers

A III-V-on-silicon bonded amplifier (left) can be used as the building block of a distributed-feedback laser (right top) and tunable laser based on microring resonators (right bottom).

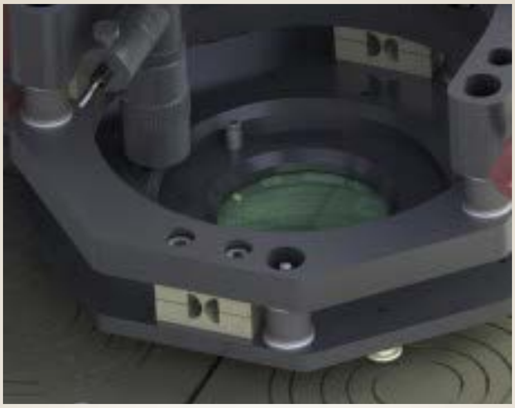
highly reflective back-reflector integrated in the silicon waveguide. The saturable absorber is integrated on top of a partially reflecting grating, ensuring that the mode-locked laser works in an anti-colliding-mode configuration, which leads to higher output power, lower timing jitter and better RF spectral purity than a colliding-pulse mode-locked laser.

A mode-locked laser featuring such a long but low-loss silicon external cavity, together with the high-quality III-V amplifier, was able to generate, at optimum bias conditions, up to 1400 laser lines, equally spaced at 1 GHz, with a 12-nm-wide, 10-dB optical spectrum. The sub-kHz 10-dB radio frequency linewidth and the narrow longitudinal mode linewidth (less than 400 kHz) indicated notably stable mode-locking. Such integrated dense comb lasers look very promising for applications such as high- resolution, real-time spectroscopy, and highlight the unique properties of the hybrid III-V–silicon platform.

Direct epitaxy of III-V on silicon

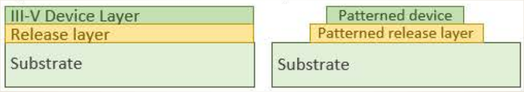
While bonding offers a versatile method for integrating dissimilar materials, direct epitaxy—growing high quality III-V layers directly on silicon—remains the ultimate dream. For high-volume applications, such a process would allow for cost reductions and added flexibility in device design. Yet direct epitaxy involves tremendous challenges. And, while researchers have worked for several decades to overcome these challenges, those efforts have long met only limited success. The success of silicon photonics, however, as well as the CMOS community's interest in using the higher mobility of III-V materials for next-generation transistors, has changed the outlook, and several research groups have reported breakthroughs in direct epitaxial growth of III-V materials on silicon within the last two years.

The biggest challenge for direct epitaxy lies in the large mismatch in lattice constant between silicon and the relevant III-V materials (4 percent with GaAs and 8 percent with InP). As a result, dislocations arise in the III-V semiconductor during epitaxial growth to compensate for this mismatch. Because those dislocations act as very efficient nonradiative-recombination sites, they tend to substantially limit the performance of an optical device. One way to reduce the impact of the lattice-constant mismatch is to grow very thick buffer layers that gradually change the lattice constant—but such thick buffer layers require a long growth time,

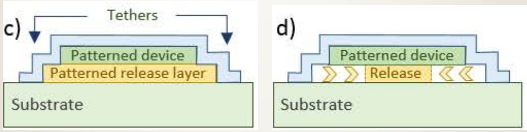


Transer printing III-V semiconductors on silicon

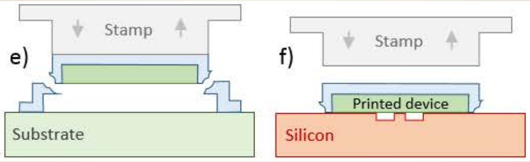
Wafer bonding, while an established integration method, can lead to inefficient use of the III-V material, and can make co-integration of different III-V semiconductor layer stacks difficult. As part of the Horizon 2020 project TOPHIT, our lab, the Tyndall National Institute, Ireland, and X-Celeprint Ltd., Ireland, are developing a new process that tackles these issues. The process rests on transfer printing of micrometer-size semiconductor chips, or coupons, from a III-V source wafer to a silicon photonic target wafer using an automated tool (see www.tophit-ssi.eu). The result could be very efficient use of the III-V source material, low-cost wafer-scale integration of such coupons and dense co-integration of different III-V materials.



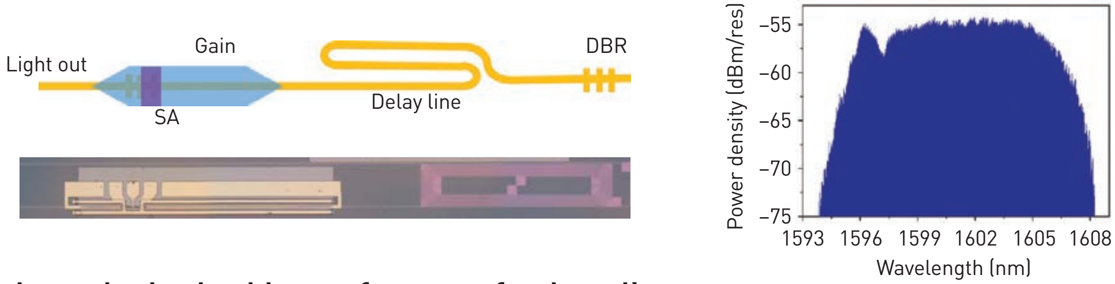
The coupons are encapsulated with a polymer and released from the substrate with a selective underetch.



Coupons are patterned in dense arrays on the III-V source wafer.



The free-standing III-V coupons are picked up with an elastomeric stamp and transferred to the silicon photonic target wafer.



A mode-locked laser from wafer bonding

A hybrid III-V–silicon mode-locked laser design (left) was able to show more than 1400 evenly spaced longitudinal modes across a 15-nm wavelength range.

which leads to increased cost, and also seem incompatible compatible with integration with other devices (such as silicon transistors and waveguides) defined in the original substrate.

Recently, independent teams at University College London, U.K. (UCL), and the University of California, Santa Barbara, USA (UCSB), demonstrated an alternative approach that can substantially reduce the buffer layer's required thickness, through the introduction of a few quantum dot layers into the buffer zone. These quantum dot layers turn out to be very efficient at bending the so-called threading dislocations downward, so that most of them do not reach the active layers, where they could affect laser operation. Quantum dots can also be used as gain media, as they have proved less sensitive to any remaining defects then more traditionally used quantum well active layers. Combining these two approaches, the UCL and UCSB teams were able to demonstrate electrically pumped lasers grown on silicon, operating at room temperature.

While quantum dot filtering layers is an effective solution to the lattice mismatch, it doesn't solve a more subtle problem arising from a different kind of material mismatch: the effort to grow a polar material, the III-V semiconductor, on a nonpolar substrate, silicon. With increasing growth time, the originally separated III-V islands have to merge, and that leads to the creation of so-called anti-phase boundaries (APB), which, like dislocations, can act as nonradiative defects and sources of optical leakage. To get around this mismatch and suppress the APBs has, thus far, required the use of special silicon substrates not used in the CMOS industry, which limits the prospects for leveraging that industry's existing tools and processes in production manufacture.

Adapting a process from electronics

In our lab's work, we have focused on an alternative approach—originally developed for realizing next-generation electronic transistors and adapted to silicon photonics—that can overcome both the lattice and polarity mismatches (see diagram on p. ??). In this approach, the III-V material is grown in small trenches defined on a standard silicon wafer, covered with a high-quality silicon oxide layer. A wet chemical etch (for example, with potassium hydroxide) exposes the (111) crystal planes of the wafer, which are very efficient in suppressing undesired APBs, while the sidewalls of the narrow, high-aspect-ratio trenches help stop detrimental dislocations from propagating further upwards.

As a result, when InP is grown in these trenches, all defects are confined in a layer a few tens of nanometer thick near the silicon-InP interface, with no defects found in the bulk of the material. The growth continues until the InP completely fills the trench, and then the wafer is planarized, an active layer (such as InGaAs) is grown on top of it, and the active layer is capped with a protective InP layer. To get to a laser device, a grating that will form the optical cavity can be added via e-beam litography. To avoid leakage of the light to the substrate, the silicon below the InP must be etched away, though this step may be avoidable by growing on conventional SOI-wafers, the standard substrates used in silicon photonics research.

Using this approach, our lab created laser structures and then tested them in a standard microphotoluminescence setup, extracting the light using a second-order grating etched in front of the actual device. The epitaxially grown sample produced lasing at a threshold pump power of 22 mW. Further, the lasing wavelength can be accurately controlled by varying the grating period. High uniformity is obtained over

The next steps for the epitaxy process developed in our labs includes growth directly on SOI wafers and working toward electrically injected devices.

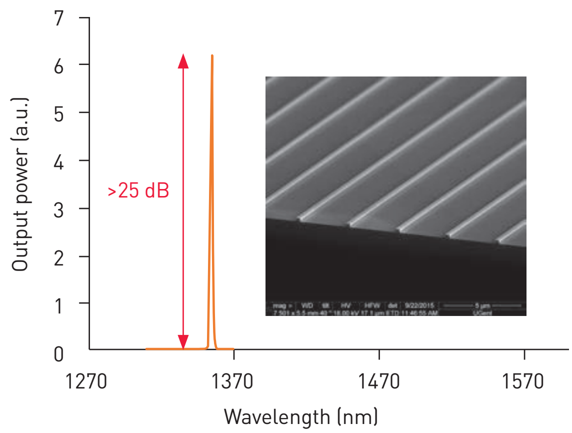
the wafer. All of this suggests that the grown material has high quality—and that it could form one approach for realizing practical lasers integrated on standard silicon substrates.

Epitaxy's next steps

The next steps for the epitaxy process developed in our labs includes growth directly on SOI wafers (to improve optical confinement and lower the thermal impedance) and working toward electrically injected devices. While the transition to SOI wafers should form no fundamental hurdle, electrical injection could be quite tricky in these sub-microscale structures. Directly depositing a metal on top of the InP-capping layer would result in excessive losses, so facilitating current injection will require different, innovative approaches.

Both the V-groove method we've developed and the use of quantum dot–based filtering layer pioneered in other labs have different strengths. The use of quantum dot layers allows growth of lasers with thick cladding, which facilitates straightforward electrical injection; on the other hand, it does not overcome the APB problem. The V-groove method, as noted above, will face challenges in electrical injection; on the other hand, because the III-V materials are only grown in the trenches where the silicon is exposed, the method makes it straightforward to combine these lasers with other devices, such as silicon waveguides, modulators or Ge-detectors, already present on the wafer. At this point it's not clear what growth technique will prevail.

What is clear is that, after a long lead-up, this field is progressing very rapidly, and the community can expect continued exciting results in the near future. For more than a decade, the lack of an efficient and scalable laser source has formed a big hurdle in advancing silicon photonics and broadening its applications. Hybrid-integration techniques relying on wafer-bonding integration of direct bandgap III-V semiconductors with silicon photonics ICs seems to have resolved this roadblock, and commercial products—incorporating increasingly complicated laser devices, expansion to new wavelength regions, and optimized bonding techniques—are already on the roadmaps of some companies. And continued progress in direct epitaxy on silicon could push the field still farther forward. OPN



Epitaxial growth with wavelength control

Lasing spectrum of InP/InGaAs device monolithically grown on silicon. The lasing wavelength can be tightly controlled by varying the grating spacing.

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