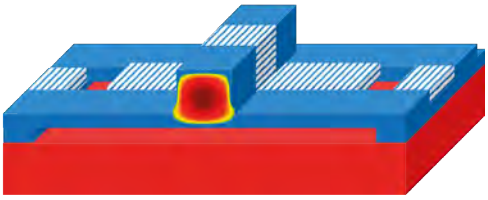
ORIENTATION-PATTERNED GALLIUM PHOSPHIDE FOR INTEGRATED NONLINEAR PHOTONICS

Konstantinos PANTZAS[1,*], Sylvain COMBRIE[2], Yoan LEGER[3], Grégoire BEAUDOIN[1], Luc LE GRATIET[1], Abdel mounaim HAROURI[1], Bruno GERARD[4], Gilles PATRIARCHE[1], Isabelle SAGNES[1], Arnaud GRISARD[2]

[1] Centre de Nanosciences et de Nanotechnologies, CNRS – Université Paris-Saclay, Palaiseau, France
[2] Thales Research & Technology, Palaiseau, France
[3] FOTON, CNRS – Université de Rennes – INSA, Rennes, France
[4] III-V Lab, Palaiseau, France
***konstantinos.pantzas@c2n.upsaclay.fr**



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Gallium phosphide has long held promise for integrated nonlinear photonics, owing to its high non-linear figure of merit, broad transparency and compatibility with silicon. The recent development of orientation patterning in gallium phosphide has now brought this promise within grasp. Current research efforts are focused on demonstrating and evaluating a variety of second and third-order non-linear processes on the platform, reducing optical losses, and investigating integration with Si.

In the past couple of decades, Silicon Photonics revolutionized Datacom by producing low-power, cost-effective photonic integrated circuits, now ubiquitous in fibre-to-the-home applications, or for rack-to-rack communications in data centres. This impressive feat was achieved by leveraging established CMOS manufacturing processes for passive circuitry and, where necessary, incorporating active optical functions, mainly laser sources, by heterogeneously integrating III-V semiconductors.

In an ongoing effort to expand the functionalities and versatility of Silicon photonic integrated circuits, one key toolbox of optics is now being integrated: nonlinear optics. Nonlinear optics covers a vast array of phenomena that depend on the intensity of light propagating through the circuit. This offers numerous and exciting new possibilities to shape, convert and mix light that holds enormous potential for new applications in quantum information or environmental and biological sensing. However, Silicon in and of itself has limited capabilities for nonlinear optics due to its vanishing second-order nonlinear coefficient induced by centrosymmetry and its band gap in the near infrared range. The convergence of nonlinear optics and Silicon Photonics can, therefore, only be achieved through the heterogeneous integration of other, highly non-linear materials.

Several materials are currently being investigated for integrated nonlinear photonics, including oxides such as lithium niobate, compound semiconductors such gallium

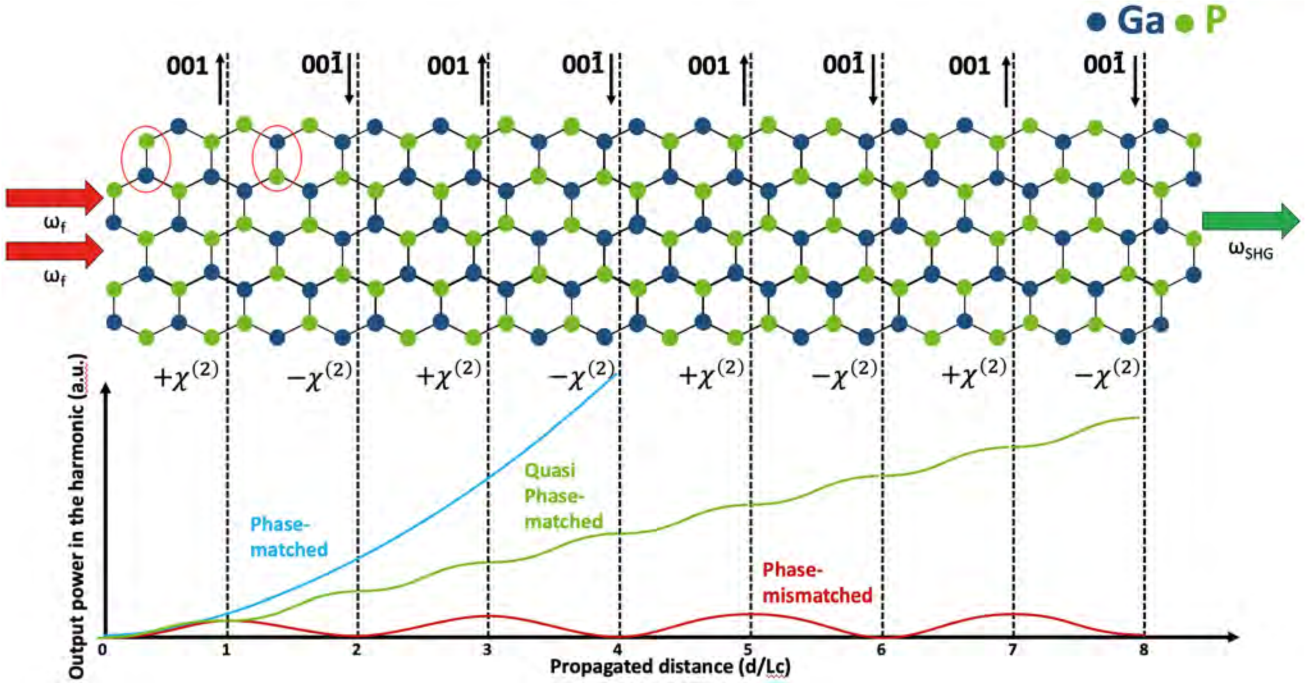

Figure 1. Second harmonic power in ideal phase matching conditions (blue), unattainable because of dispersion. Without orientation reversal, phase mismatch periodically eliminates the SHG signal (red). With orientation reversal the mismatch is compensated and the SHG power progressively builds up (green).

arsenide or aluminum gallium arsenide, and alloys of silicon and germanium. Lithium niobate, in particular, currently leads the race for integrated nonlinear photonics, owing to significant progress in the production and transfer of thin films of the material, the fabrication of waveguides and the relative ease with which quasi-phase matching is achieved in it, using a process called periodic poling.

However, the jury is still out on the final choice of material. Gallium phosphide, a compound semiconductor mostly reserved to the fabrication of red light-emitting diodes till now, has started garnering attention owing to a slew of remarkable properties. Indeed, it possesses high second and third-order nonlinear coefficients, a high refractive index, ● ● ●

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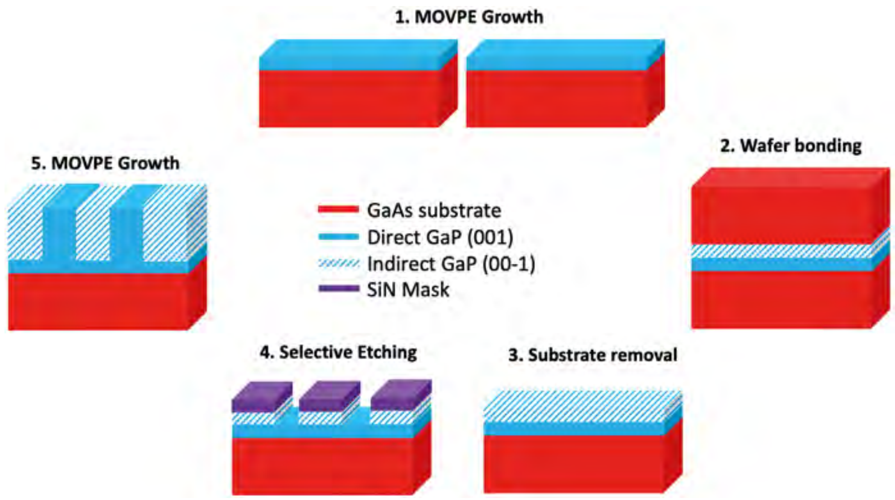


Figure 2. Schematic representation of the fabrication of Orientation-Patterned Gallium Phosphide. The orientation is reversed when the left wafer is flipped and bonded on the first.

a broad transparency from the visible to the mid-infrared, and, in regards to integration, benefits from negligible lattice and thermal mismatch with silicon [1].

Possessing high non-linear coefficients is only the first step towards a nonlinear photonic platform using gallium phosphide. Nonlinear optical processes involve mixing at several optical waves at vastly different wavelengths. Since nonlinear crystals are dispersive, one needs to eliminate the phase mismatch between the different waves contributing to the wave-mixing process. In tabletop nonlinear optic experiments, the phase mismatch can be eliminated in a variety of manners by adjusting the optical elements of the setup to use birefringence, for instance. This is, however, not feasible on a photonic integrated circuit. Instead, the nonlinear crystal itself needs to be molded in a manner that eliminates phase mismatch (see Figure 1).

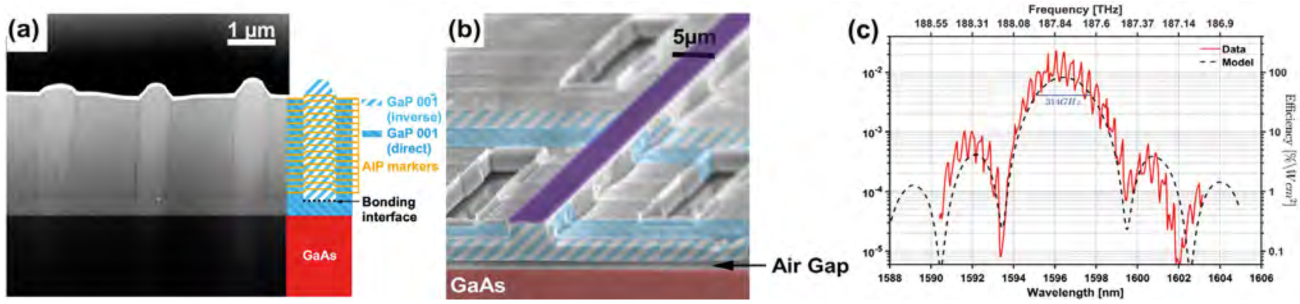
ORIENTATION PATTERNING

Phase matching within the nonlinear crystals can be achieved in a variety of manners. Amongst these, quasi phase matching through the periodical reversal of the crystal orientation is the most versatile and useful for integration, as the period of reversal provides the degree of freedom necessary to counterbalance the constraints imposed by photonic integrated circuits. Periodic poling, the common way of establishing orientation reversal in lithium niobate that consists in applying an electric field on MgO-doped domains of lithium niobate to induce the orientation reversal, is one of the reasons this material has been so successful. Periodic poling cannot be applied to gallium phosphide and other compound semiconductors, however: the iono-covalent bonds of these crystals are so strong that the voltage required for periodic poling is higher than their breakdown voltage.

An alternative approach, better suited to compound semiconductors, is orientation patterning [2]. This technique uses a combination of cleanroom processes that allows one to produce a crystal seed with the orientation-reversal period of choice. The typical process flow is described in Figure 2. Thin membranes of Gallium Phosphide are grown on sacrificial Gallium Arsenide substrates using metal-organic chemical vapour epitaxy. These two templates are then bonded together using direct fusion wafer bonding, creating a stack that contains both orientations of GaP. After removing the top substrate, the orientation-reversal period is etched into the GaP stack, using e-beam lithography and ICP etching. This creates a crystal seed of orientation-patterned GaP (OP-GaP), that can then be grown to the desired thickness [3].

Orientation patterning has been applied to a variety of compound semiconductors, but it has revealed itself to be particularly well suited

Figure 3. (a) Cross-sectional view of OP-GaP, observed in transmission electron microscopy; (b) OP-GaP waveguide; (c) Efficiency curve for SHG in an OP-GaP waveguide; adapted with permission from Reference [3]. Copyright 2022 American Chemical Society.



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to gallium phosphide: the boundaries between domains of alternating crystal orientation are perfectly vertical from the very first nanometre of regrowth, to the surface. This property, known as domain fidelity, lends itself well to photonic integration of nonlinear functions, as it allows one to make almost arbitrarily thin waveguides of OP-GaP, significantly increasing the overlap between pump, signal and idler waves and drastically decreasing the size of the nonlinear element.

WAVEGUIDE FABRICATION

A sample OP-GaP waveguide is shown in Figure 2. It is a shallow-ridge waveguide 3 µm high, 5 µm wide, and 1 mm long. The substrate beneath the waveguide was selectively etched away using openings on the sides, creating a suspended membrane that 20 µm wide and 1 mm long. Thus, the final waveguide is air-clad, maximizing the index contrast and making the most of the high refractive index of GaP. At these dimensions, OP-GaP waveguides are already very competitive for photonic integration of nonlinear functions – provided that they yield a sufficiently high conversion efficiency.

The performance of such OP-GaP waveguides for nonlinear photonics was benchmarked against competing technologies using second-harmonic generation experiments. Specifically, OP-GaP air-clad, shallow-ridge suspended waveguides such as the ones described above and with an orientation-reversal period of 5.5 µm were used to convert telecom C-band light into visible light. The conversion efficiency curve in Figure 3 shows a record conversion efficiency of $200\ \%/\mathrm{Wcm}^2$ - five hundred times higher than GaP waveguides that do not use orientation patterning [4]. These early demonstrations showcase the promise of OP-GaP waveguides for integrated nonlinear photonics – provided they can be reliably transferred on Si photonic circuitry.

INTEGRATION

Given its negligible lattice and thermal-expansions mismatch with silicon, GaP – and, by extension, OP-GaP – can be integrated on Si-photonic platforms using a variety of methods, including wafer bonding or hetero-epitaxy. In large integration schemes, however, nonlinear functions are expected to be required only in specific areas of the photonic integrated circuit – hence wafer-scale transfer of OP-GaP is not necessary. Furthermore, different nonlinear functions would require the integration of OP-GaP waveguides of different sizes and orientation-reversal periods. A more localized approach to photonic integration seems to be better suited for this particular technology.

In light of this information, micro-transfer printing appears as the most promising approach. In this technique, coupons are picked from their initial substrate and transferred onto their intended space on a photonic integrated circuit with extremely precise positioning. This technique was recently applied to transfer waveguides of GaP [5]. The dimensions of the chips hosting the transferred waveguides were 60 µm by 6 mm, similar to those of the OP-GaP waveguides discussed above. Furthermore, the suspended-membrane approach is strikingly similar to the architecture required to use micro-transfer printing, reinforcing the argument in favour of employing micro-transfer printing • • •

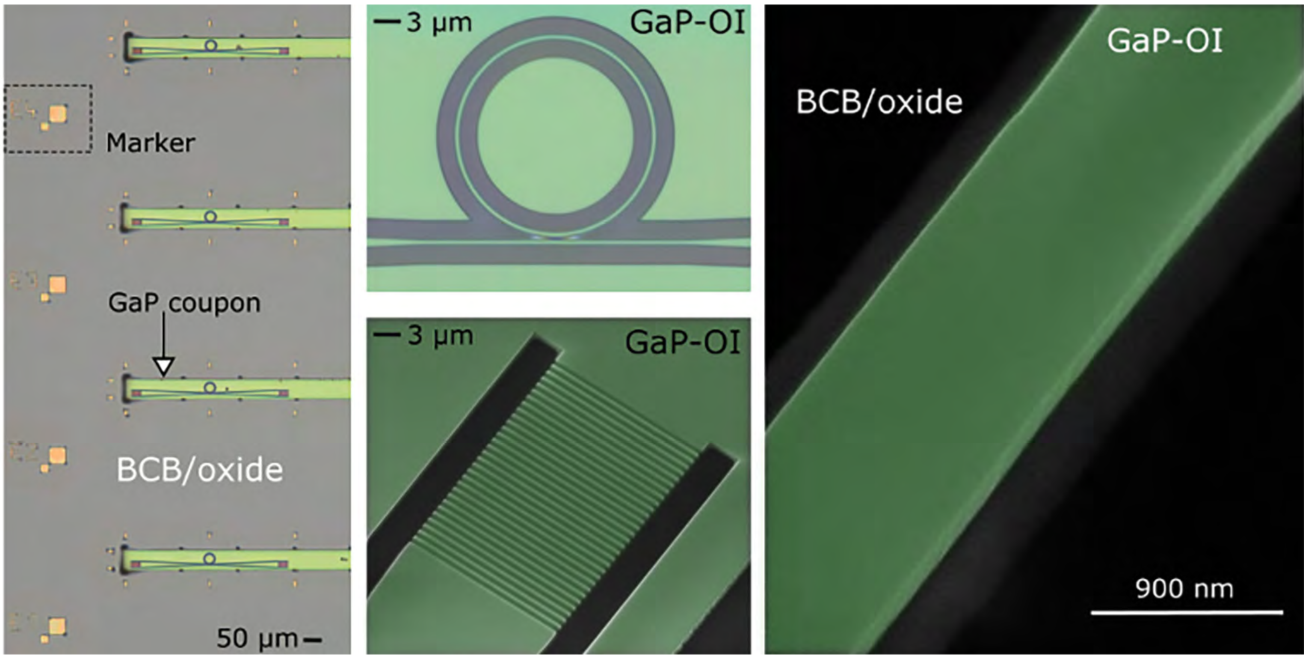

Figure 4. Scanning electron micrographs of GaP coupons with transferred onto Si using microtransfer printing. The coupons contain a GaP waveguide with a micro-ring resonator and injection couplers at the ends. Final image shows a close-up view of the smooth surface of GaP after transfer. From Reference [5]

to integrate OP-GaP on Si photonic integrated circuits.

CONCLUSION

The integration of nonlinear optical functions on Silicon photonic integrated circuits will bring forth a slew of new applications in spectroscopy, telecommunications, quantum cryptography, and quantum computing. Given the constraints of photonic integration, including the complexity of existing photonic integrated circuit architectures and the available on-board optical power, the circuit element that operates the nonlinear function needs to be made in a material that has a high nonlinear figure of merit, can be tailored to match a specific process and can be readily engineered into compact waveguides that decrease its footprint. Orientation-Patterned Gallium phosphide is an emerging material platform that meets all three of these criteria and promises to foster the convergence of nonlinear optics and silicon photonics. Still in its first stages of development, OP-GaP already presents itself as a viable alternative to competing technologies. Though still shy of the performance boasted by PPLN, OP-GaP has the potential to far surpass all competitors as its complex fabrication process matures and is optimized. Ultimately, one could envision OP-GaP as a single material platform for integrated nonlinear photonics, producing elements tailormade for a variety of applications, and ready to be picked and placed on any desired photonic integrated circuit. ●

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