Optical Materials EXPRESS

Hybrid Photonics: Integration, Design and Devices: feature issue introduction

SÉBASTIEN CUEFF,[1] JOYCE POON,[2,3] DRIES VAN THOURHOUT,[4] AND LAURENT VIVIEN[5]

[1] *CNRS, Ecole Centrale de Lyon, INSA Lyon, Universite Claude Bernard Lyon 1, CPE Lyon, INL, UMR5270, 69130 Ecully, France*
[2] *Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany*
[3] *Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, Ontario M5S 3G4, Canada*
[4] *Photonics Research Group, Ghent University-IMEC, Belgium*
[5] *University Paris Saclay, CNRS, Centre for Nanoscience and Nanotechnology (C2N), Palaiseau, France*

Abstract: We introduce the *Optical Materials Express* feature issue on *Hybrid Photonics: Integration, Design and Devices.* This issue comprises a collection of ten papers including six invited and four contributed papers from well-established research groups and prominent scientists in the field. These papers cover the development, characterization, control, technologies and applications of hybrid devices for photonics.

Research in Optics has always been a matter of exploiting the most efficient materials for specific functionalities, from transparent glasses in lenses and optical fibers, to optoelectronic devices including direct bandgap III-V semiconductors for lasers and electro-optical materials for modulators. In the world of macroscopic devices and systems, integrating such optical functionalities from different technological platforms has never been a problem in itself and rather consists of properly shaping, packaging and connecting them.

Then came silicon photonics, which revolutionized the field of optics by revisiting CMOS processes, exploiting silicon to guide and process light at the micro- and nano-scale, paving the way for the co-integration of electronics and photonics on the same chip. The combined advantages of wafer-scale production provided by existing foundries, and the high optical contrast between silicon and its natural oxide, SiO_2, made silicon a dream platform for integrated optics. After a few decades of progresses, designs and technologies have reached industrial maturity and silicon photonics devices and systems are commercialized for various applications. However, despite its technological maturity, silicon remains silicon, with a limited potential for light modulation and emission.

It is now clear that future efficient integrated photonic circuits should include other, optically active, materials, in the silicon photonics platform. The co-integration of functional materials with silicon promises ultra-efficient devices and systems with unique properties, such as non-volatile reconfigurable properties for neuromorphic computing or sensing, as well as efficient light sources and modulators for beam-steering. Although this co-integration sounds like an ideal way to take the best of both worlds, the road ahead is paved with challenges of compatibility in fabrication or function. This is in essence a multidisciplinary domain, requiring expertise in material science, chemistry, solid-state physics, electrical engineering, multi-physics design and nanofabrication.

This feature issue contributes to cover these different aspects, to explore and define future devices and systems leveraging functional materials for integrated optics.

In this regard, the numerous scientific questions are only one side of the coin. Indeed, the economic aspects and commercial perspectives are just as important for the future implementation

#522692 https://doi.org/10.1364/OME.522692
Journal © 2024 Received 28 Feb 2024; published 1 May 2024

Optical Materials EXPRESS

of these hybrid technologies. This is the complex question addressed in an *Opinion Paper* by Roel Baets and Abdul Rahim [1]. In this paper, they describe the opportunities and challenges offered by the heterogeneous integration in foundries and how the industry would need to evolve in future years to reach viable solutions. One market that appears particularly promising for hybrid platforms is neuromorphic computing. In that context, Xu et al. provide an extensive review of different materials platforms for on-chip neuromorphic computing [2].

From a more technological point of view, the integration process itself needs to be revisited, and Ranno et al. propose a scheme and a process flow for the integration of multi-materials based on 3D photonic platform [3]. As the current cleanroom fabrication technologies may also evolve and welcome new fabrication tools, Nguyen et al. propose the use of nanoimprint lithography as a cost-effective method for potentially large-scale patterning of Perovskite materials and apply it to demonstrate polaritonic metasurfaces [4].

Functional oxides present unique electro-optic modulation properties that could strongly boost integrated optical modulators. In this feature issue, three papers leverage functional oxides for different applications. While Yun Fang et al. [5] design multi-functional metasurfaces for the terahertz wavelength range using the insulator-to-metal transition (IMT) of vanadium dioxide (VO_2), Wang et al. [6] make use of Lithium Niobate to design anisotropic metasurfaces with tunable circular dichroism. Seoane et al. [7] combine VO_2 with the ferroelectric oxide $BaTiO_3$, the former being exploited to modulate the amplitude of light while the latter leveraged to tune the optical phase. Such a combination could lead to efficient building blocks for neuromorphic computing.

Chalcogenide compounds, which are well-known phase-change materials (PCM) have been also considered because they present very large differences in refractive index between their amorphous and crystalline phases. Here, three papers exploit the exciting properties of an emerging PCM: Sb_2S_3. This chalcogenide, together with Sb_2Se_3, features a large optical contrast between its amorphous and crystalline states while keeping negligible optical absorption (i.e. loss) in both states. Gutierrez et al. [8] leverage the optical modulation of this material to design Brewster angle optical switch. Taute et al. [9] propose and demonstrate a simple method to program PCM layers to arbitrary levels of partial crystallization, paving the way for future multi-level non-volatile programmable devices. Up to now, the optical properties of this material were only known in the visible and near-infrared ranges. In this issue, Bieganski et al. [10] demonstrate that Sb_2S_3 also presents negligible optical loss in the mid-infrared, making it a promising PCM for future applications in this wavelength range.

We hope that you will find this *Optical Materials Express* feature issue on *Hybrid Photonics: Integration, Design and Devices* an interesting and useful reference and that it will impact and stimulate further advances in the field.

References

1. R. Baets and A. Rahim, “Heterogeneous integration in silicon photonics: opportunities and challenges: opinion,” Opt. Mater. Express **13**(12), 3439–3444 (2023).
2. R. Xu, S. Taheriniya, A. P. Ovvyan, *et al.*, “Hybrid photonic integrated circuits for neuromorphic computing [Invited],” Opt. Mater. Express **13**(12), 3553–3606 (2023).
3. L. Ranno, J. X. B. Sia, K. P. Dao, *et al.*, “Multi-material heterogeneous integration on a 3-D photonic-CMOS platform,” Opt. Mater. Express **13**(10), 2711–2725 (2023).
4. N. H. M. Dang, P. Bouteyre, G. Trippe-Allard, *et al.*, “Nanoimprinted exciton-polaritons metasurfaces: cost-effective, large-sale, high homogeneity, and room temperature operation [Invited],” Opt. Mater. Express 14, in press (2024).
5. X. Zhang, S. Yan, S. Peng, *et al.*, “Tunable terahertz multi-functional hybrid-patterned metasurface arrays based on vanadium dioxide,” Opt. Mater. Express **13**(11), 3173–3186 (2023).
6. L. Wang, F. Setzpfandt, and I. Shadrivov, “Tunable anisotropic electro-optic metasurfaces,” Opt. Mater. Express **13**(11), 3376–3383 (2023).
7. J. J. Seoane, J. Parra, J. Navarro-Arenas, *et al.*, “Enhanced $BaTiO_3/Si_3N_4$ integrated photonic platform with VO_2 technology for large-scale neuromorphic computing [Invited],” Opt. Mater. Express **13**(11), 3266–3276 (2023).
8. D. Pérez-Francés, G. Santos, J. Resl, *et al.*, “Sb_2S_3-based optical switch exploiting the Brewster angle phenomenon [Invited],” Opt. Mater. Express **13**(12), 3677–3687 (2023).
9. A. Taute, S. Al-Jibouri, C. Laprais, *et al.*, “Programming multilevel crystallization states in phase-change-material thin films,” Opt. Mater. Express **13**(11), 3113–3120 (2023).

Optical Materials EXPRESS

10. A. Bieganski, M. Perestjuk, R. Armand, *et al.*, "Sb_2S_3 as a low-loss phase-change material for mid-IR photonics [Invited]," Opt. Mater. Express **14**(4), 862–870 (2024).